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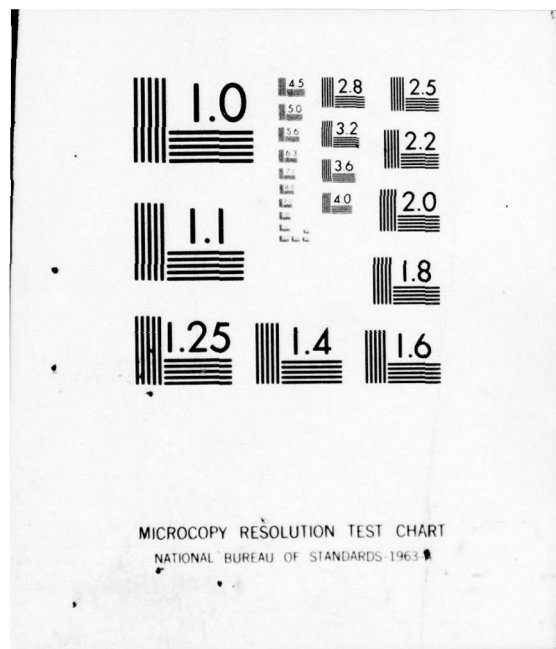
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AERIAL OBSERVATIONS OF OCEANIC FRONTS IN
THE WESTERN MEDITERRANEAN SEA

by

Robert E. Cheney

U. S. NAVAL OCEANOGRAPHIC OFFICE
WASHINGTON, D. C. 20373

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ABSTRACT

The western Mediterranean Sea and Gulf of Cadiz were surveyed during the period 30 April to 19 May 1976 to study the distribution and physical characteristics of oceanic fronts. Three hundred seventy temperature profiles were obtained from airborne expendable bathythermographs dropped during eight flights. Synoptic temperature fields were constructed from these data to determine regions of large horizontal gradients. Because the ultimate goal of these studies is to examine the effect of oceanic fronts on underwater sound, Mediterranean fronts were defined as coherent, recognizable boundaries separating different acoustic regimes. These regimes were defined on the basis of variation in sonic layer depth and sound channel depth--two parameters whose acoustic impact is reasonably well understood. In order for a feature to qualify as a front, it was required that one or both of these quantities change 50 m or more across a horizontal distance of 25-35 km.

Of the survey areas, only the Alboran Sea and Ionian Sea contained fronts which were significant, coherent, and directly associated with the pattern of thermal gradients. (The Maltese Front was intentionally omitted due to limited flight time and the abundance of existing data.) The Alboran Sea Front meandered from Gibraltar eastward through the entire basin and separated the basin into two acoustic regimes: north of the front temperatures at 100 m were 1-2°C cooler and both sonic layer and sound channel depths were about 100 m shallower than on the south side. The frontal feature observed in the Ionian Sea was the result of a northward intrusion of warm water in which the sound channel was substantially deeper than values found elsewhere (240 m versus 100 m); because of intense surface heating there was no corresponding change in sonic layer depth.

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1. INTRODUCTION

The Mediterranean Sea is a region of obvious strategic importance, especially with regard to naval operations and antisubmarine warfare (ASW). It is therefore desirable to gain as complete an understanding as possible of the role played by the environment in acoustic systems performance and detection capabilities. Among the many factors to be considered are oceanic fronts. With the exception of the Maltese Front southeast of Sicily, which has been studied extensively (Allan *et al.*, 1974; Briscoe *et al.*, 1974; Johannessen *et al.*, 1971), little is known of Mediterranean fronts. The first step, then, is to determine their distribution and character.

With this objective in mind, an aerial survey was conducted in the western Mediterranean and Gulf of Cadiz during the period 30 April to 19 May 1976. Thermal gradients were delineated using airborne expendable bathythermographs (AXBT's). All regions of the Mediterranean between Gibraltar and Sicily were included in the study, with one flight being devoted to the Ionian Sea. This report presents analyses of these data and also includes a brief summary of the Mediterranean's circulation and water mass distribution (Appendix A).

2. METHODS

Eight flights were conducted out of Rota, Spain and Sigonella, Sicily. Three hundred seventy AXBT's were dropped at approximately 30 nm spacings. The Magnavox AXBT provides a temperature profile to a depth of 350 m and, for the range of temperatures encountered during these flights, has an accuracy of 0.1-0.3°C (Sessions *et al.*, 1976).

Data presented in this report have been divided into two groups of four flights each as shown by flight tracks and AXBT drop positions in figures 1 and 4. The westernmost areas, surveyed during the period 30 April to 8 May 1976, include the Gulf of Cadiz, Alboran Sea, Algerian Basin, and the Balearic Basin. The remaining regions, studied during 10-19 May, include the Ligurian Sea, Tyrrhenian Sea, Sicily Straits, and the Ionian Sea. Although the Maltese Front is a region of interest, it was intentionally omitted due to limited flight time and the existence of a thorough ship/aircraft survey conducted in May 1971 (Briscoe *et al.*, 1974).

3. DEFINING A MEDITERRANEAN FRONT

Before discussing these results, it would be helpful to define exactly what a Mediterranean Sea front is. This unfortunately turns out to be a difficult problem. An oceanic front is a boundary between two regimes with many different characteristics which, among other things, include temperature, salinity, sound speed, sonic layer depth, and sound channel depth. Because there are many different types of fronts, a variety of criteria have been used to define them. Cheney and Winfrey (1976) provide a broad definition in terms of acoustics: "A front is any discontinuity in the ocean which significantly alters the pattern of sound transmission and propagation loss.

Thus a rapid (horizontal) change in depth of the sound channel, a difference in sonic layer depth, or a temperature inversion would denote the presence of a front." This helps define the problem, but the question remains: How large does a horizontal gradient have to be in order to be significant?

There seems to be little doubt that major frontal systems such as the Gulf Stream and Kuroshio have a measurable impact on underwater sound propagation (Gemmill, 1974; Levenson and Doblar, 1976). However, these fronts exhibit horizontal gradients which are larger and extend much deeper than those found in the Mediterranean. Although Levine and White (1972) observed frontal zones in the eastern Mediterranean with gradients as large as 2°C per km (excessive even for the Gulf Stream), these were restricted to the upper 50 m and were caused by changes in the seasonal thermocline depth of only 20 m. Such fronts are of questionable acoustic importance and would undoubtedly weaken or disappear altogether in winter when the seasonal thermocline is destroyed.

Sonic layer depth (SLD) is well understood in terms of acoustic impact and changes on the order of 50 m are probably sufficient to significantly alter sound propagation. In addition to the effect created by a horizontal change in SLD, it is important to know which side of a front will normally exhibit the deeper or shallower layer depth. Information of this nature can be used to formulate both avoidance and detection techniques. Moreover, fronts such as the Maltese Front or the Sargasso Sea Front (Voorhis, 1969), which have very small thermal gradients associated with them, often separate regions of radically different SLD.

Sound channel depth (SCD) is also directly related to underwater sound propagation. Throughout the Mediterranean a sound channel occurs just beneath the main thermocline at depths of 50-250 m. Since the thermocline represents the boundary between Atlantic and Mediterranean Waters, sound channel depth is determined largely by the thickness of the Atlantic Water layer. Regions of the Mediterranean in which the Atlantic layer is unevenly distributed exhibit horizontal changes in SCD. As with SLD, fluctuations in SCD of about 50 m in a short distance may be important.

Because these two parameters are known to have a measurable impact on sound propagation, it is appropriate to use them in the description of fronts. We therefore define a Mediterranean front as a coherent, recognizable boundary separating different acoustic regimes as characterized by SLD and SCD. In order for an oceanic feature to qualify as a front, we require that one or both of these parameters change 50 m or more along a relatively short horizontal distance (25-35 km). Such a gradient is probably sufficient to significantly alter sound propagating through the front. Further, an ASW unit transiting such a frontal zone would, within the period of an hour, move into a region with drastically different local acoustic conditions. Although it is customary to define Mediterranean fronts in terms of their horizontal temperature gradients, the acoustic effect of these gradients themselves, unaccompanied by SLD or SCD gradients, is not clear. The temperature field will therefore not be considered to be the primary frontal feature, but merely a possible indication of an "acoustic front", which we have defined here in terms of the parameters SLD and SCD.

4. RESULTS OF THE SURVEY

Synoptic temperature maps, provided in Appendix B, include analyses at the surface and at depths of 100, 200, and 300 m. When feasible, data in adjacent areas were smoothed together in an attempt to present uninterrupted temperature maps. The resulting maps are not totally synoptic in themselves, but represent a synthesis of several thermal "snapshots" taken over two nine-day periods. Representative temperature sections from seven of the basins are shown in Appendix C.

Because the emphasis of this study is on the acoustic effect of fronts, the important maps are those showing distributions of SLD and SCD (Figs. 2, 3, 5, and 6). SLD was computed from each AXBT by assuming constant salinity and converting temperature profiles to sound speed profiles.¹ SLD was then defined as the first sound speed maximum below the surface. Depth of the sound channel was calculated in a similar fashion. The sound channel is defined as the absolute minimum in the sound speed profile, above and below which the speed increases. Because the deep Mediterranean is so nearly homogeneous, pressure causes sound speed to increase all the way to the bottom from its minimum value just below the main thermocline.

Maps of SLD in Figs. 2 and 5 reveal that, with the exception of the Gulf of Cadiz and Alboran Sea, layer depths are generally shallow (less than 5 m) over broad areas with maximum depths occasionally reaching 30 m. This results in correspondingly small horizontal changes in SLD. In the Gulf of Cadiz and Alboran Sea, however, SLD varies dramatically, ranging from 0 to 180 m over relatively short distances.

SCD distributions in Figs. 3 and 6 indicate significant horizontal gradients in the Alboran Sea, Algerian Basin, and the Ionian Sea. SCD in these areas ranges from 80 to 240 m. Elsewhere in the western Mediterranean horizontal changes are small. In the Gulf of Cadiz the sound channel is deeper than 350, the maximum depth of the AXBT probe, and could not be determined.

Maps of SLD and SCD thus indicate four regions which exhibit gradients of the magnitude required to qualify as acoustic fronts: The Gulf of Cadiz, Alboran Sea, Algerian Basin, and the Ionian Sea. They are considered individually below.

¹This procedure is valid during spring and summer; during other seasons, however, the constant salinity assumption can lead to errors of about 25 m in the calculation of SLD.

Gulf of Cadiz - The Gulf is a special case for two reasons. The first is that it is outside the Mediterranean proper; Atlantic Water occupies the upper 500-800 m above the more dense Mediterranean Water. As in the Mediterranean, a sound channel exists at the interface between these two water masses, but this boundary is well below the maximum depth sampled by the AXBT. Although significant variations in SCD may exist, they cannot be determined from these data.

A second problem is that many of the temperature profiles obtained in the Gulf of Cadiz during the 30 April survey have gradients in the upper 200 m which produce nearly vertical sound speed profiles (speed constant with depth). SLD is therefore not well-defined and small changes in the shapes of the temperature profiles can cause large SLD differences. Although the map of SLD in the Gulf of Cadiz (Fig. 2) shows large horizontal gradients, the distribution is unstable and shows no apparent relationship to the pattern of thermal gradients (Figs. B1-B4). This is a case in which SLD variation is not representative of a frontal phenomenon. Reasonably strong horizontal gradients of temperature (0.03°C per km) are found at all depths between the surface and 300 m, however, without accompanying changes in SLD or SCD their acoustic significance is questionable.

Alboran Sea - SLD and SCD display horizontal gradients in the Alboran Sea which are both strong and coherent. Furthermore, these two quantities seem to be closely related to each other and to the surface and 100 m temperature fields (Figs. B1 and B2). The pattern which emerges shows a front which meanders from Gibraltar eastward through the entire Alboran Sea. North of the front temperatures at 100 m are $1-2^{\circ}\text{C}$ cooler and both SLD and SCD are about 100 m shallower than on the south side.

This pattern is a reflection of the varying thickness of the Atlantic surface layer. Geostrophic currents calculated by Lanoix (1974) and Ovchinnikov *et al.*, (1976) for the Alboran Sea reveal the existence of an anticyclonic gyre just inside the Strait which dominates circulation between Gibraltar and Cape Tres Forcas at 3°W (Fig. 7). This feature also appears in surface current measurements obtained by Lacombe *et al.*, (1964) and Grousson and Faroux (1963). Atlantic Water flows around the northern half of the gyre and continues eastward in a relatively narrow, meandering stream. This current divides the Alboran into two regions with the thicker surface layer of Atlantic Water being found on the south side. North of the front the layer is thin and the thermocline is shallower, thereby reducing SLD and SCD and producing cooler temperatures. In the sonic layer map of figure 2 the largest horizontal gradients are found around the anticyclonic gyre, where SLD changes from 40 to 180 m in only 35 km. The gyre is also well defined by SCD distribution, but the most pronounced gradient occurs further downstream at 1°W where SCD changes from 100 to 220 m in only 40 km.

In summer, upwelling along the southern coast of Spain produces strong surface temperature gradients which enhance the main features of the Alboran Sea circulation. During this time satellite infrared imagery can be used to infer currents in this region and estimate the location of the front. The example shown in Fig. 8 clearly shows the anticyclonic cell in the western

Alboran. In this photo, which also includes the Gulf of Cadiz, lighter areas represent colder temperatures. Similar patterns were found to persist throughout the summers of 1975 and 1976 (Eubanks *et al.*, 1977). Mommmsen (1976) compared simultaneous XBT and satellite infrared data and concluded that surface temperature gradients do, in some cases, provide indications of sub-surface features that may be of significance to ASW operations.

Algerian Basin - SLD varies only from 0 to 30 m in the Algerian Basin and there are no significant SLD gradients. The SCD distribution, however, shows isolated pockets of alternating shallow (100 m) and deep (200 m) sound channels with strong horizontal gradients. The pattern does not appear as coherent as that of the Alboran and there is no obvious relation of SCD to the temperature maps in Appendix B. Although there is still a distinct boundary between the Atlantic and Mediterranean Waters in the Algerian Basin the eastward flowing surface current may be neither strong nor concentrated enough to create a recognizable frontal effect. A more accurate method of determining the variation in depth of the Atlantic/Mediterranean interface is to map the depth of a constant salinity surface in the main halocline. Had salinity data been available it may have been possible to better explain these large SCD gradients. From the data presented here, it can be stated that large SCD gradients of the type associated with fronts were observed in the Algerian Basin, but that the underlying mechanism responsible for their existence is not clear.

Ionian Sea - Like the Algerian Basin, the Ionian Sea displays shallow SLD's and small gradients (Fig. 5). The map of SCD, however, reveals a deep sound channel protruding northward from the Gulf of Sirte along 19°E (Fig. 6). DSC changes from 240 inside the intrusion to 100 m outside. A similar feature was observed in this area by Anderson *et al.*, (1973). The intrusion corresponds to a tongue of warm water in the 100 m temperature map (Fig. B6). Atlantic surface water flows through the Sicily Strait and eastward along the north coast of Africa into the Ionian Sea. The warm water tongue is apparently a branch of this flow, suggesting that the southern Ionian Sea may possess a more extensive frontal system than shown here. This possibility is supported by observations of other fronts in the Ionian Sea (Gilcrest, 1973; Levine and White, 1972).

5. CONCLUSIONS

By defining Mediterranean fronts in terms of sonic layer depth and sound channel depth, two parameters whose acoustic impact is reasonably well understood, it was determined that frontal features existed in only four areas of the western Mediterranean; the Gulf of Cadiz, Alboran Sea, Algerian Basin, and the Ionian Sea. Of these areas only the Alboran Sea and Ionian Sea contained fronts which were significant, coherent, and directly associated with the pattern of thermal gradients. Although the Maltese Front was deleted from the survey because of extensive studies conducted previously, it is also considered to be an important acoustic front.

The Alboran Sea Front was found to meander from Gibraltar eastward through the entire basin. It separated the basin into two acoustic regimes: north of the front temperatures at 100 m were 1-2°C cooler and both SLD and SCD were about 100 m shallower than on the south side. This phenomenon is believed to be caused by differences in thickness of the surface layer of Atlantic Water which occur on opposite sides of the North African Current.

The frontal features observed in the Ionian Sea appeared to be part of a larger frontal system, particularly when results of previous observations in this region are considered. The data reveal a northward intrusion of warm water in which SCD was substantially deeper than values found elsewhere (240 m versus 100 m). There was no corresponding change in SLD. The warm tongue apparently consists of modified Atlantic water which flows through the Sicily Strait and along the African coast.

The Algerian Basin contained isolated pockets of alternating shallow (100 m) and deep (200 m) sound channels which created strong horizontal gradients. Although this may be indicative of frontal activity, there was no apparent relationship of this distribution to the temperature field. In the Gulf of Cadiz, large SLD gradients were caused more by slight variations in the initial slope of the temperature profiles than by true frontal features; SCD, which occurs between 500-800 m, could not be determined from the AXBT's. Other areas surveyed (Ligurian Sea, Balearic Basin, Sicily Straits, Tyrrhenian Sea) displayed no significant horizontal gradients of SLD or SCD, even though moderately strong thermal gradients existed in some cases.

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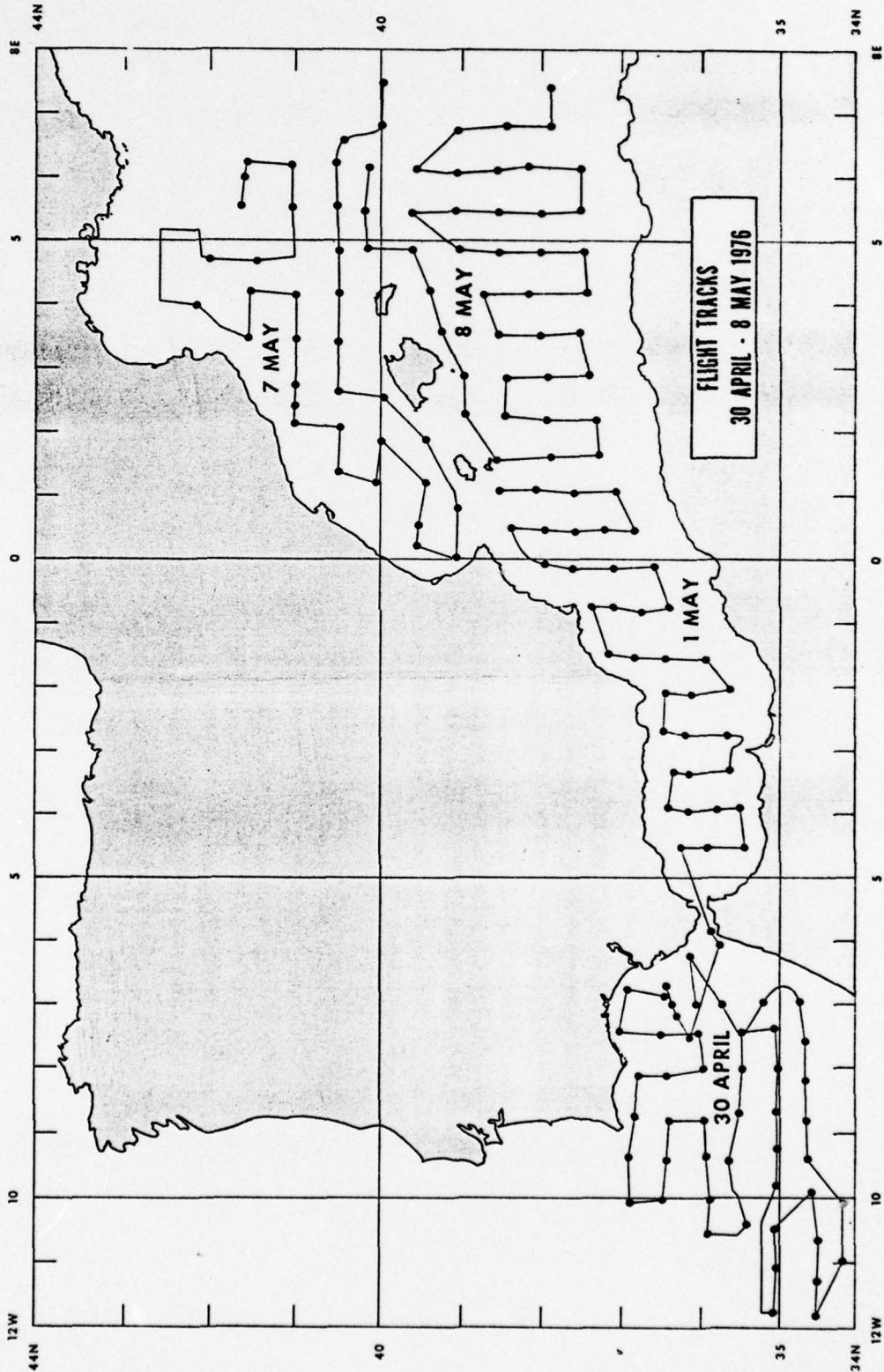


Figure 1 - Flight tracks and AXBT positions, 30 April to 8 May 1976.

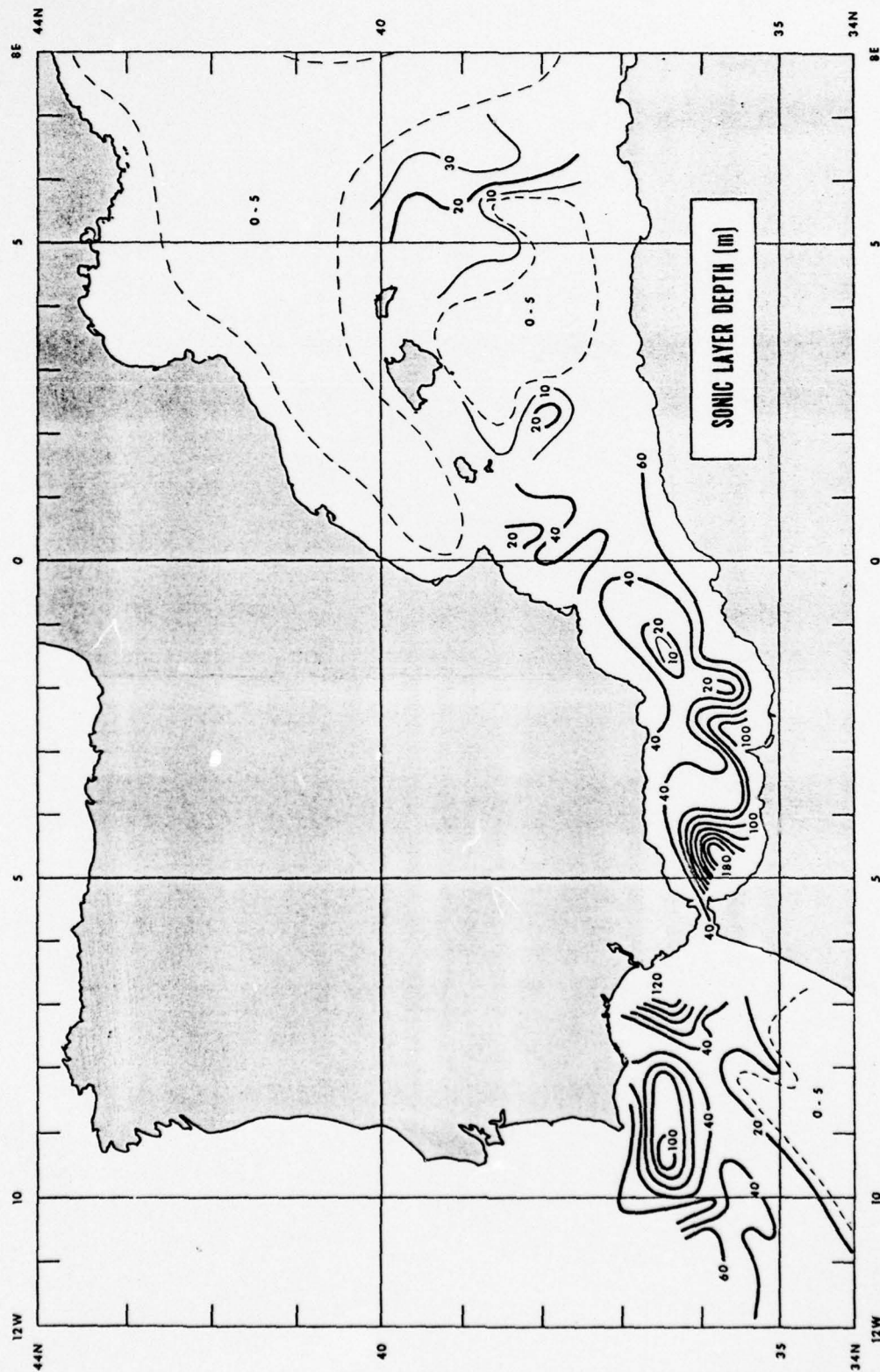


Figure 2 - Sonic layer depth, 30 April to 8 May 1976.

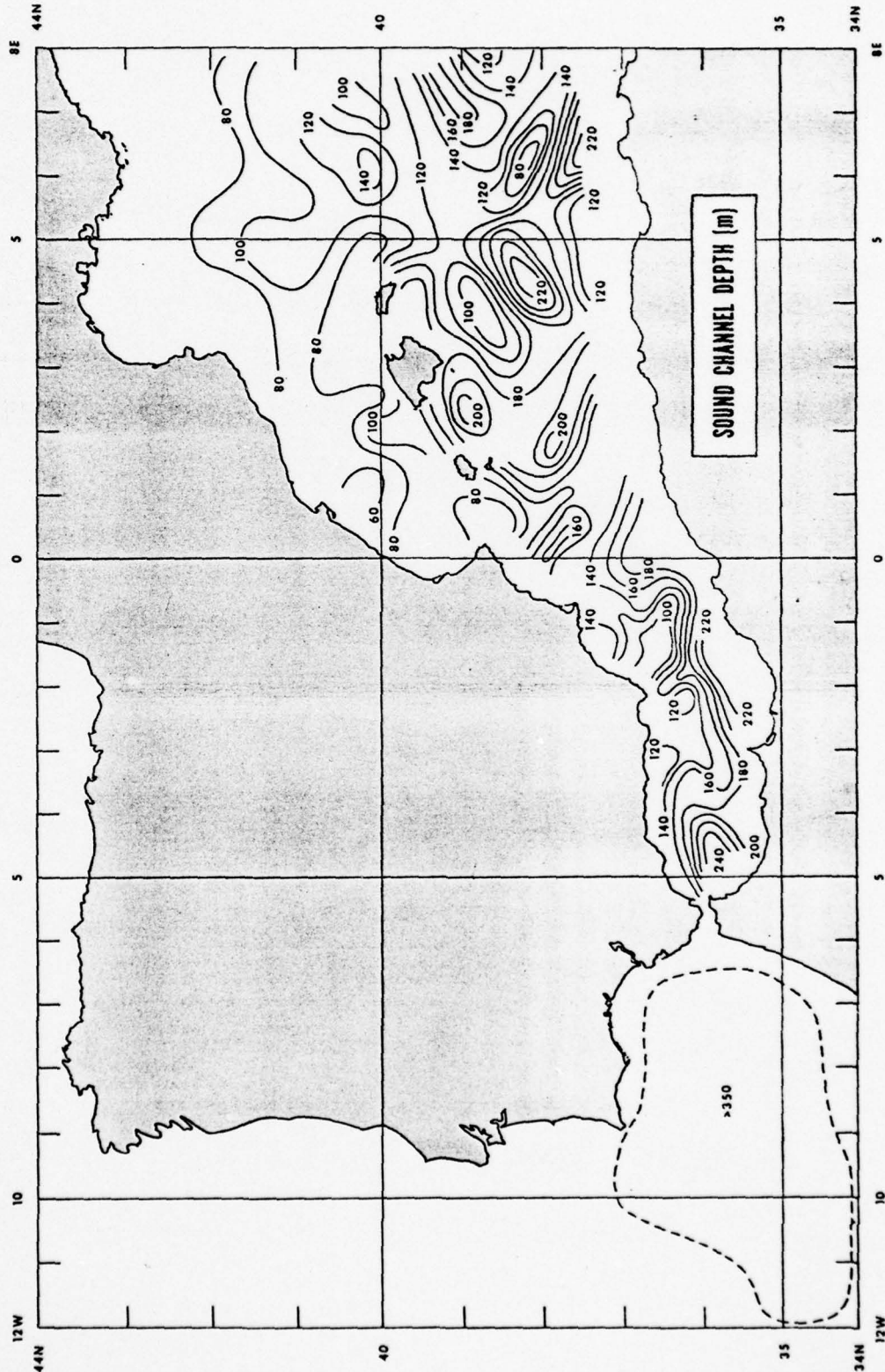


Figure 3 - Sound channel depth.

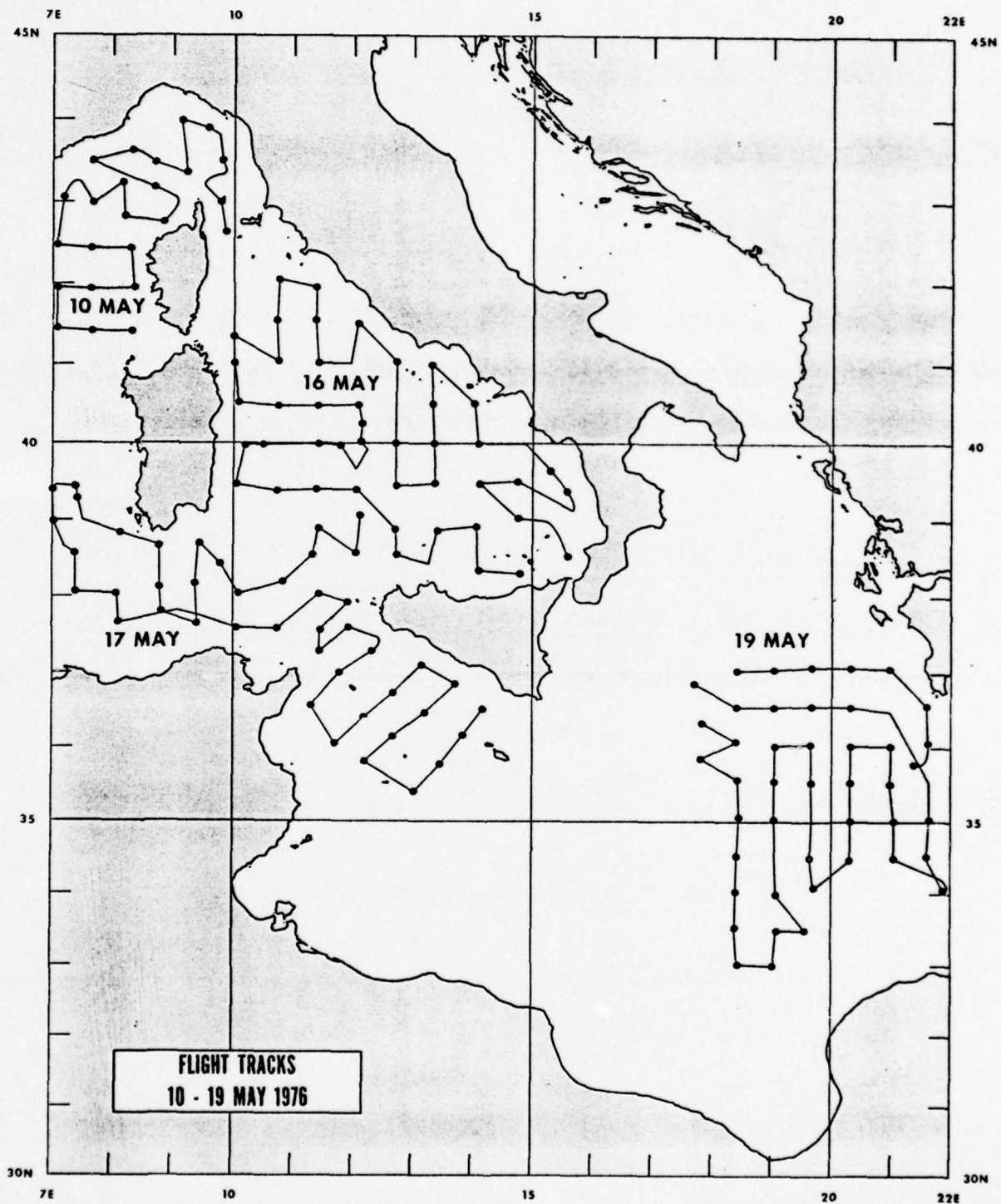


Figure 4 - Flight tracks and AXBT positions, 10-19 May 1976

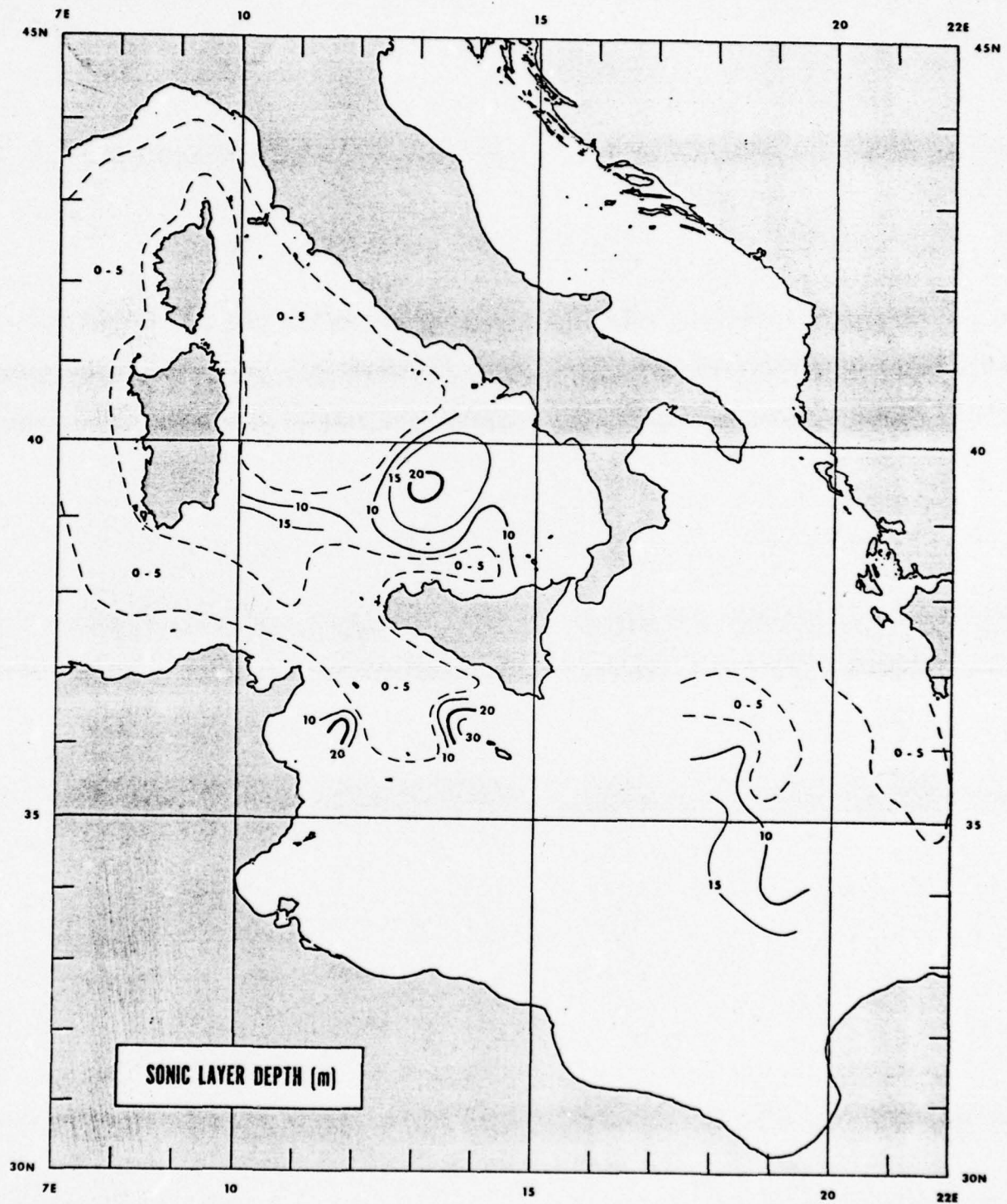


Figure 5 - Sonic layer depth, 10-19 May 1976.

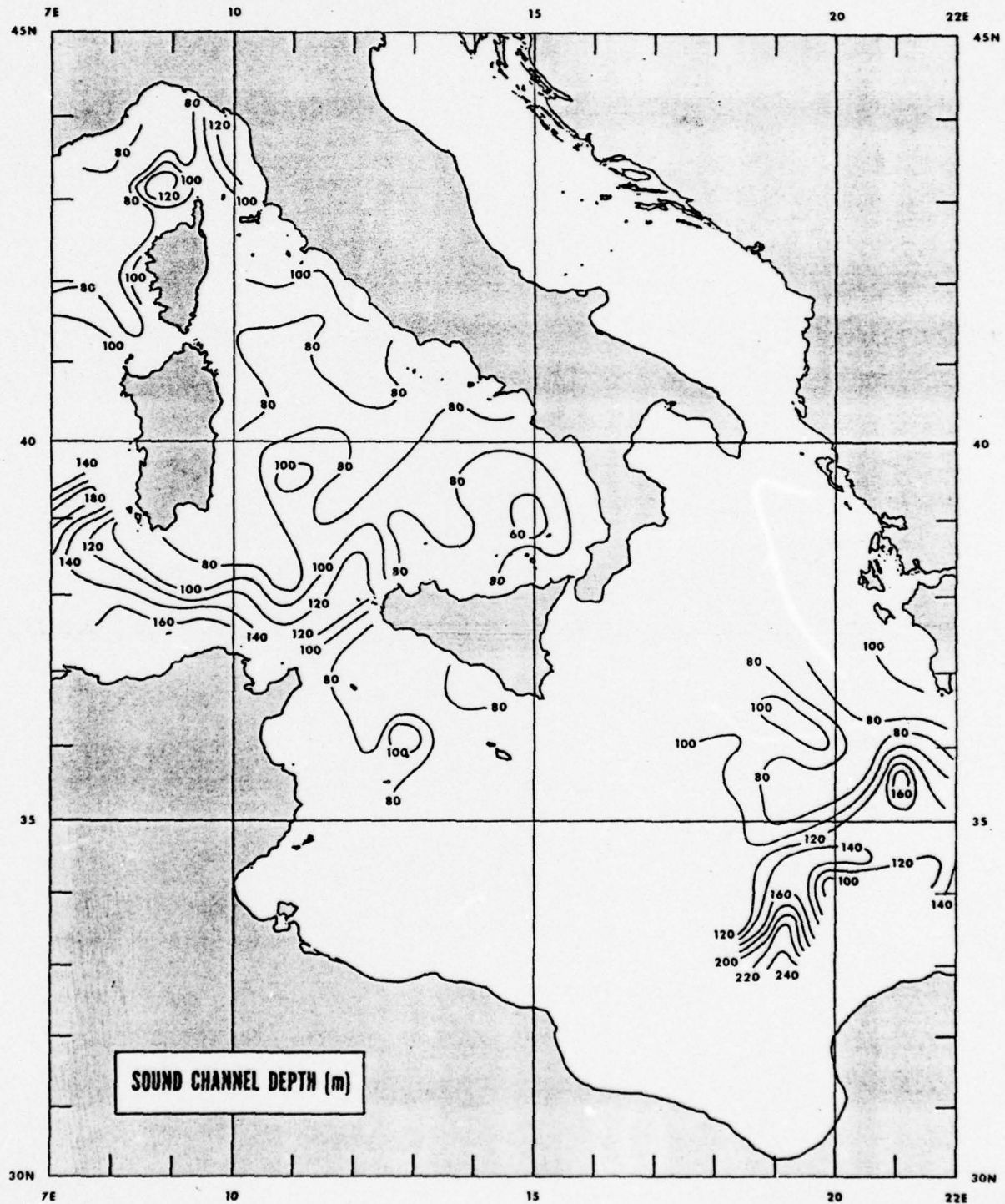


Figure 6 - Sound channel depth, 10-19 May 1976,

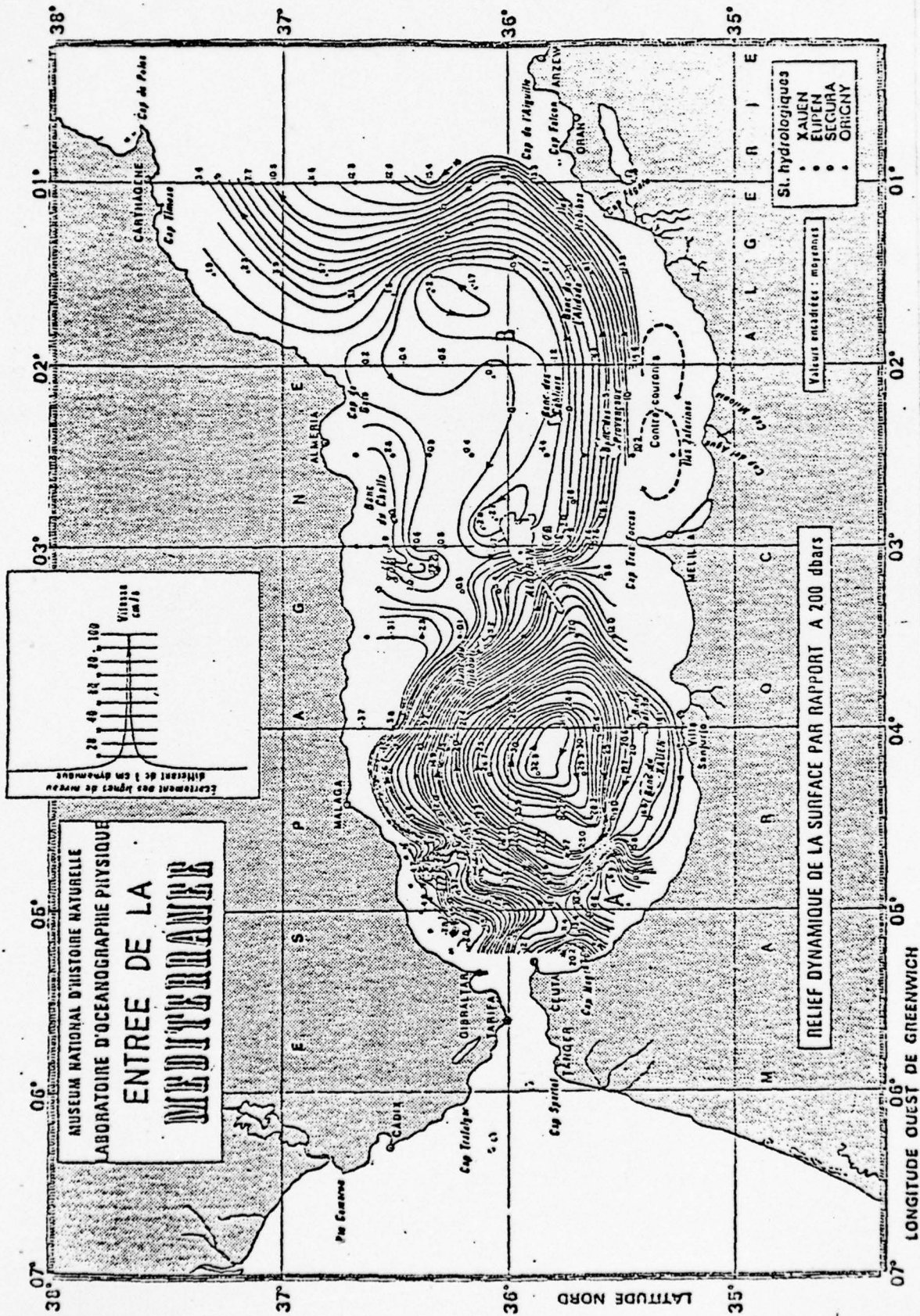
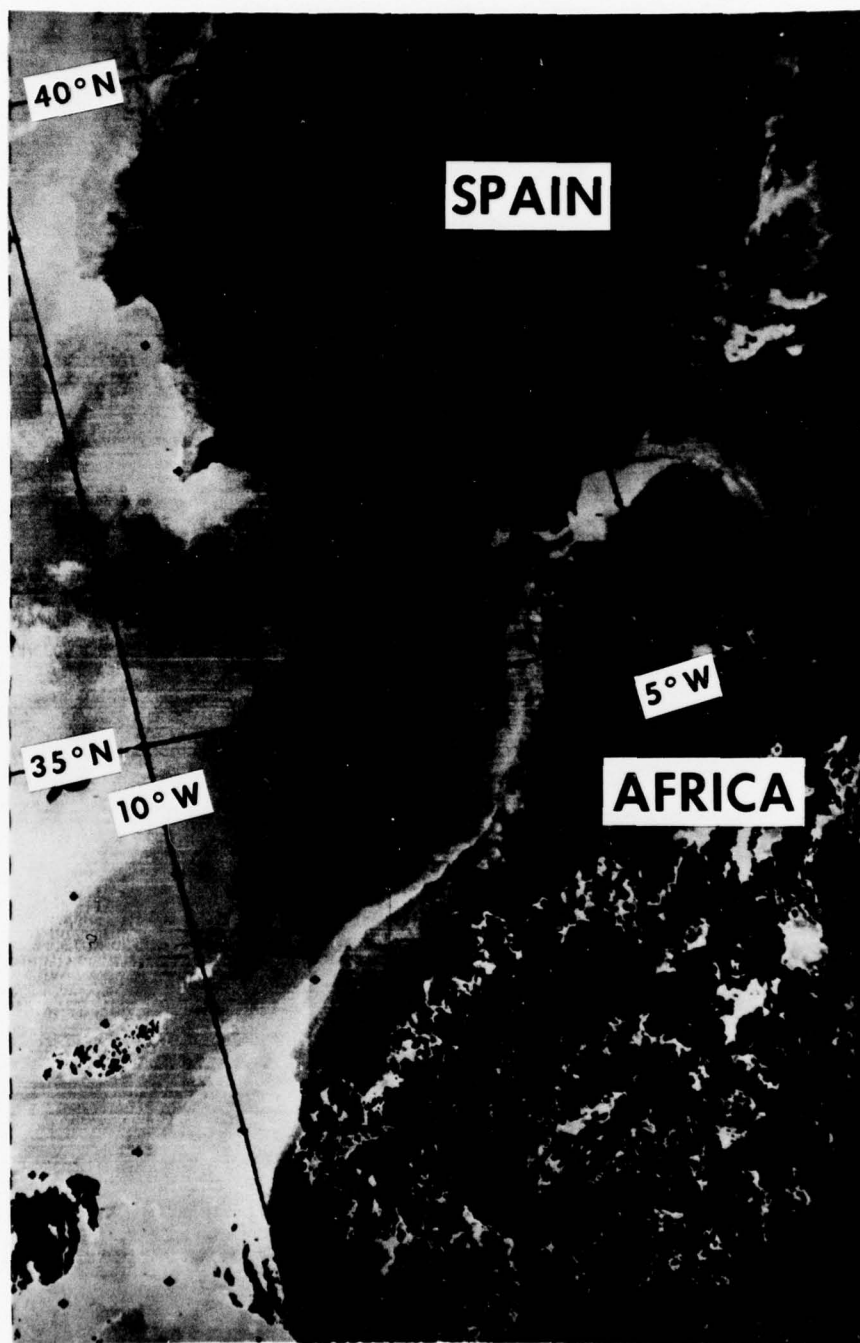


Figure 7 - Dynamic topography of the surface relative to 200 dbars.



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Fig. 26 - Infrared image obtained on 24 July 1975 by the Defense Meteorological Satellite. Areas shown are the Gulf of Cadiz and Alboran Sea. Lighter shades represent cooler surface temperatures. Upwelling in the Alboran Sea along the southern coast of Spain is entrained into the anticyclonic gyral.

APPENDIX A

PHYSICAL ASPECTS OF THE MEDITERRANEAN SEA

1. Water and salt budget

The Mediterranean Sea is a concentration basin; the amount of fresh water lost by evaporation exceeds the gain from rivers and precipitation. This imbalance would result in a decrease in sea level of 0.75 cm per year and a gradual increase in average Mediterranean salinity were it not for transport through the Strait of Gibraltar (and the Bosphorus Strait to a much lesser extent). The sea level deficit is made up by a net inflow in the upper 200 m through the Strait of Gibraltar of approximately 1750 km^3 per year (Lacombe and Tchernia, 1971). Excess salt is removed from the Mediterranean by a highly saline outflow below 200 m. Water in the Mediterranean Sea is thus largely Atlantic Water which has been modified by physical processes within the various Mediterranean basins. Residence time of a parcel of water, calculated by dividing the volume of the Mediterranean by the total inflow, is about 100 years.

2. Circulation

Although the overall water and salt budget of the Mediterranean is relatively simple due to the limited factors involved, its internal circulation is more difficult to summarize. Ovchinnikov (1966) computed geostrophic currents for the entire Mediterranean by evaluating all available information on the hydrology of the sea. One thousand m was chosen as the level of no motion since below this depth horizontal density gradients in the Mediterranean are very small. Figure A1 shows the resulting circulation pattern during winter. At the surface the North African Current flows from the Strait of Gibraltar eastward along the Algerian coast and continues through the Sicily Strait into the eastern Mediterranean. The rest of the surface circulation is composed of cyclonic gyres in the various basins to the left of the North African Current and, in a few instances, small anticyclonic gyres to the right.

The intermediate circulation shown in Figure A1 coincides closely with the surface flow except for a countercurrent from Tripoli to Gibraltar. Levantine Intermediate Water, which originates in the extreme eastern Mediterranean, apparently flows westward toward Sicily through a complicated series of gyres; after passing through the Sicily Strait it turns north into the Tyrrhenian Sea and emerges south of Sardinia. The intermediate current then splits into north and south branches, one contributing to the cyclonic cell south of France and the other forming the countercurrent beneath the incoming North African Current. The two branches meet in the Alboran Sea and ultimately empty into the Atlantic.

Swiftest currents in the Mediterranean are found in the Strait of Gibraltar, where the incoming Atlantic Water reaches speeds of 100 cm s^{-1} . Average speed of the North African Current in the upper 150 m of the western basin is $5 \text{ to } 15 \text{ cm s}^{-1}$, decreasing from west to east. The countercurrent flowing toward Gibraltar just beneath the Atlantic Water has a maximum speed of approximately 5 cm s^{-1} at 200 to 300 m. Elsewhere in the Mediterranean current direction is maintained with depth and speeds are slightly higher. Circulation in the various cyclonic and anticyclonic gyres is on the order of $10 \text{ to } 25 \text{ cm s}^{-1}$ in the upper layer (0 to 150 m) and $5 \text{ to } 10 \text{ cm s}^{-1}$ at intermediate depths (150 to 400 m).

The pattern of circulation in the Mediterranean varies little from season to season, however, current strength is reduced by about half in summer. Surface currents are predominantly wind-driven and are controlled by northwesterly winds which exist throughout much of the year. The many islands, sills, and irregular coastlines also play a major role in determining current flow.

3. Development of Mediterranean water masses

As mentioned previously, the Mediterranean is composed of Atlantic Water which has been modified by the environment over the period of many years to form "Mediterranean Water". Within this broad category the Mediterranean may be broken down into three basic layers: modified Atlantic Water in the upper 150 m, Levantine Intermediate Water between depths of 150-400 m, and Deep Water below 400 m. Because the average depth in the Mediterranean is 1500 m, Deep Water comprises about three-fourths of the total volume. The evolution of these three separate layers can be illustrated by looking at the processes occurring during the different seasons.

Atlantic Water flowing in through the Strait of Gibraltar is warmer, fresher, and consequently less dense than Mediterranean Water. It is distributed throughout the various Mediterranean basins in a thin surface layer 100-200 m thick. In summer this water is modified in a way that will prepare it for the more radical transformation it will undergo in winter. First surface heating creates a strong seasonal thermocline at about 50 m and as summer progresses, evaporation increases the salinity of the surface layer above the thermocline. Because the thermocline inhibits vertical mixing, Atlantic Water immediately below the thermocline remains largely unchanged. Summer climatology thus leads to the establishment of a warm, saline, surface layer above the thermocline with a layer of cooler, fresher water immediately below. Temperature and salinity of these shallow layers varies from one basin to the next with salinity generally increasing to the east. For example, the salinity minimum below the thermocline is 36.16‰ at Gibraltar but reaches a high value of 38.9‰ in the eastern Mediterranean (Lacombe and Tchernia, 1971).

The Mediterranean climate in winter is characterised by cold, dry winds that cool the surface and further increase salinity of the upper layer by evaporation. Increasing surface density eventually produces vertical mixing which rapidly destroys the seasonal thermocline. In the Levantine basin between Egypt and Cyprus the highly saline (39.5‰) surface layer mixes with

the remaining Atlantic Water just below the thermocline to form a homogeneous water mass (15.5°C, 39.1‰) between the surface and 250 m (Morcos, 1972). This water, known as Levantine Intermediate Water, spreads westward throughout the Mediterranean where it is generally found between 150-400 m. By the time it reaches the western basin mixing has altered its temperature and salinity to 13.4°C and 38.5‰.

Deep Water in the eastern Mediterranean has its origins in the Adriatic. Here cold shelf water (11°C) mixes downward to the bottom in winter to form a nearly homogeneous water mass. This water flows into the deep Ionian and Levantine basins where its temperature and salinity are typically 13.6°C and 38.7‰ (Miller, et al., 1970).

In the western Mediterranean, Deep Water formation is restricted to a small region south of France. In January a region of high density is usually found near the surface in the vicinity of 42°N, 5°E. Then in February, the strong, cold winds of the Mistral produce violent mixing; in a two week period the mixed layer increases from 0 to 2000 m (Stommel, 1972). This water (12.8°C, 38.4‰) spreads throughout the western basin below depths of 400 m.

Most of the Mediterranean thus consists of nearly homogeneous Deep Water with temperature and salinity ranges of 13.0-13.6°C and 38.4-38.7‰. Above this is the Levantine Intermediate Water, easily identifiable by its salinity maximum. Significant horizontal gradients in the Mediterranean are therefore restricted to the upper 200 m and it is here that oceanic fronts would be expected to occur.

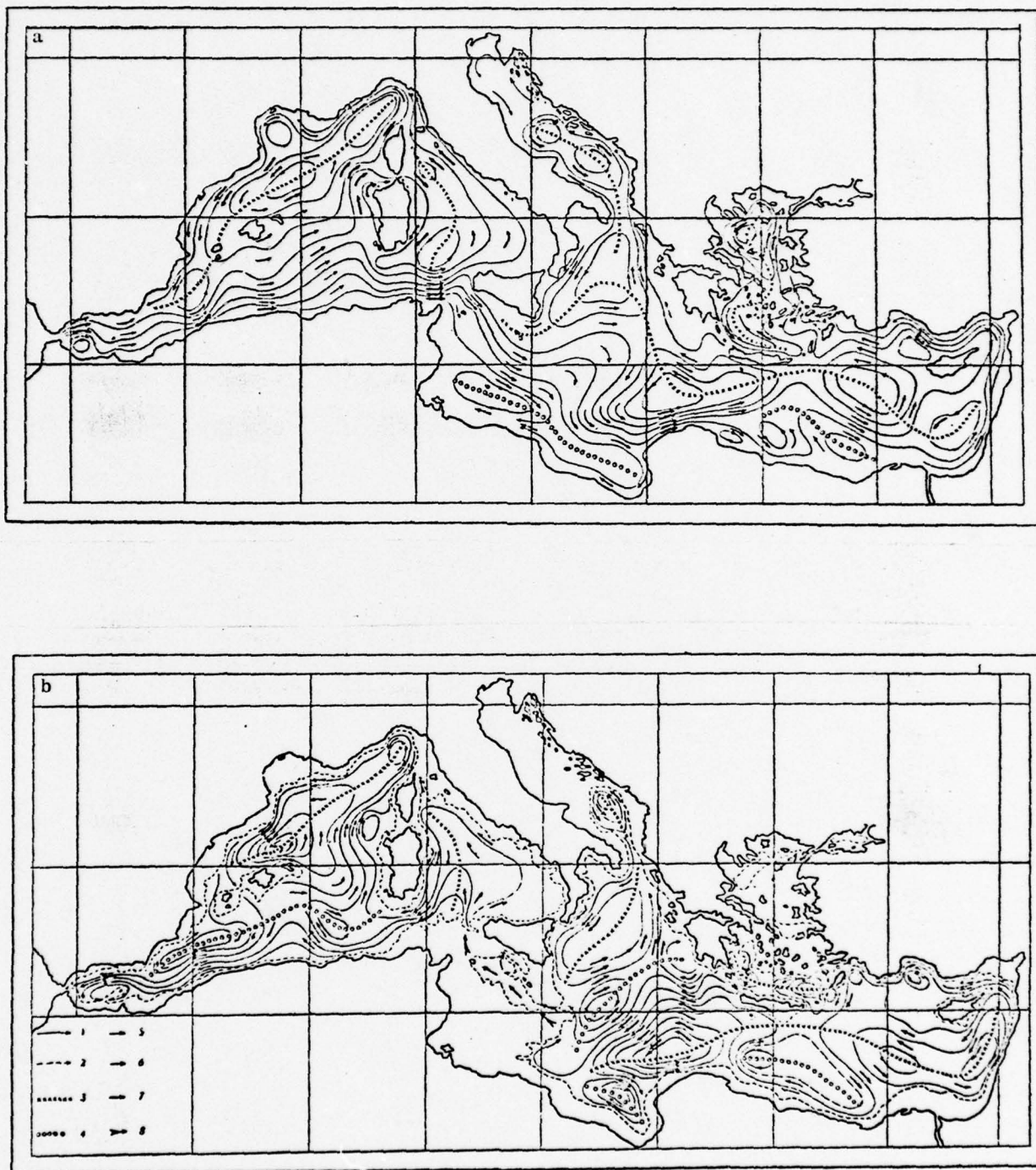


Figure A1 - Geostrophic components of Mediterranean currents in the winter
a) at the surface, b) at 500 m. (From Ovchinnikov, 1966).

APPENDIX B

SYNOPTIC TEMPERATURE MAPS

Figures B1-B8 present isotherms at the surface and at depths of 100, 200, and 300 m. The large scale trend indicated by these temperature maps is one of gradual warming toward the east. This is most pronounced at the surface where temperatures increase from 15-16°C in the Alboran Sea to 19-20°C in the Ionian. This effect is due in part to the difference in sampling dates (the Alboran survey preceeded the Ionian by 18 days). Further, because the net flow at the surface is from west to east, waters of the easternmost regions have been exposed to the warmer Mediterranean climate for a longer period of time. This zonal warming trend is also apparent at 200 and 300 m where the temperature increase between Gibraltar and the Ionian is about 2°C. In this instance, however, we are sampling Levantine Intermediate Water, which mixes with deeper waters and becomes cooler as it flows westward.

The strongest horizontal gradients in the Mediterranean appear in the surface and 100 m analyses; gradients at 200 and 300 m are weak throughout. This is in agreement with the premise that significant frontal features would be found only in the upper layer of Atlantic Water. In the Alboran Sea and south of Sicily gradients are especially strong at a depth of 100 m while in the Balearic Basin, Ligurian Sea, and Tyrrhenian Sea the largest gradients are found at the surface. Large horizontal temperature differences in the Ionian Sea are apparent at both of the upper levels. Throughout these basins frontal features appear as both meandering currents and eddy-like pockets of cold and warm water.

The Gulf of Cadiz is a special case, being outside the Mediterranean proper. Dense Mediterranean Water flows out the Strait and along the continental rise in a layer centered at about 1200 m (Zenk, 1970). The upper 500 to 800 m of the Gulf consists of Atlantic Water with its broad main thermocline. Variations in the depth of the thermocline thus produce large thermal gradients at all levels between the surface and 300 m, as shown in Figures B1 through B4.

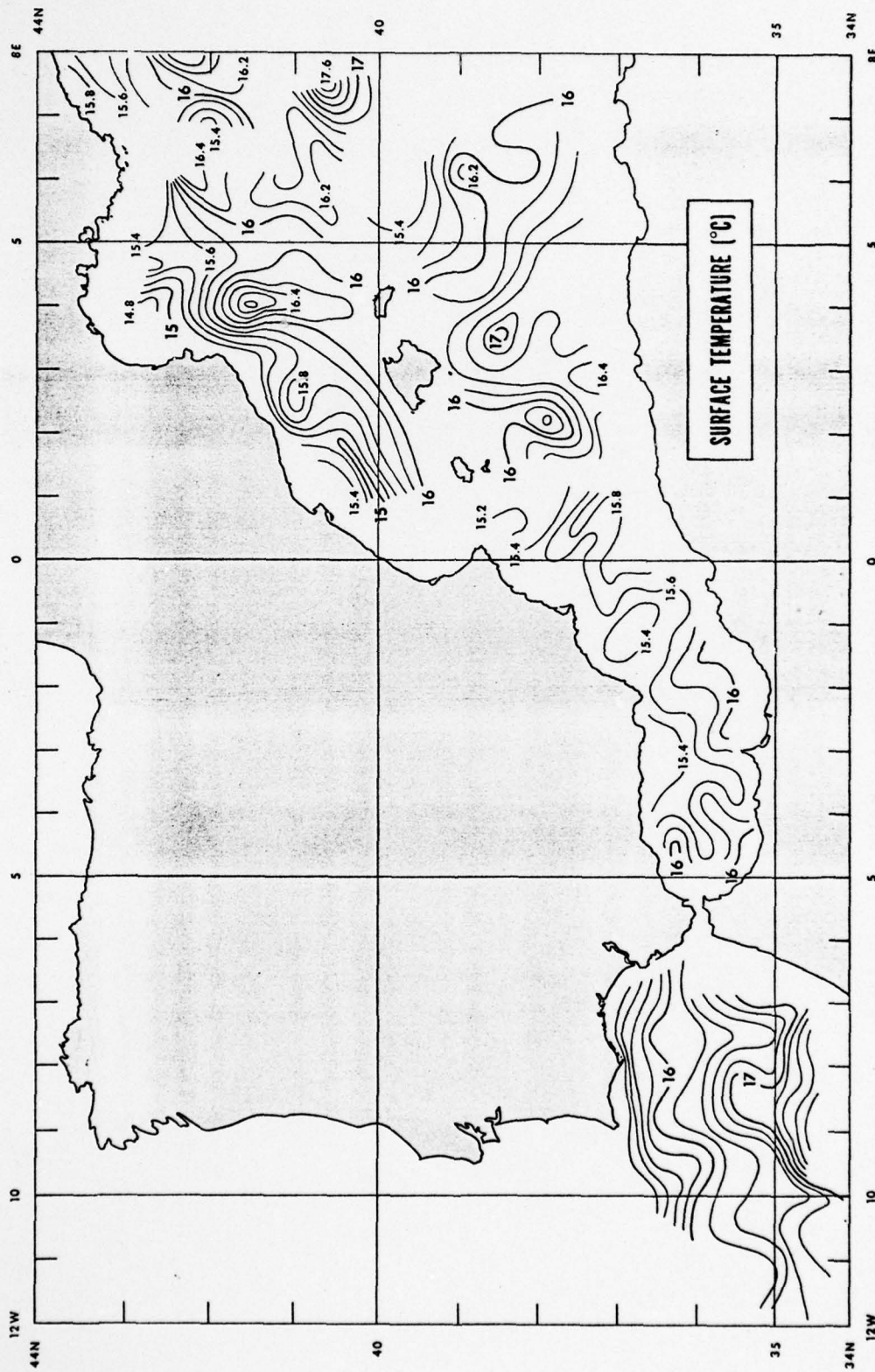


Figure B1 - Surface temperature determined from AXBT's 30 April to 8 May 1966.
Isotherms are at 0.2°C intervals.

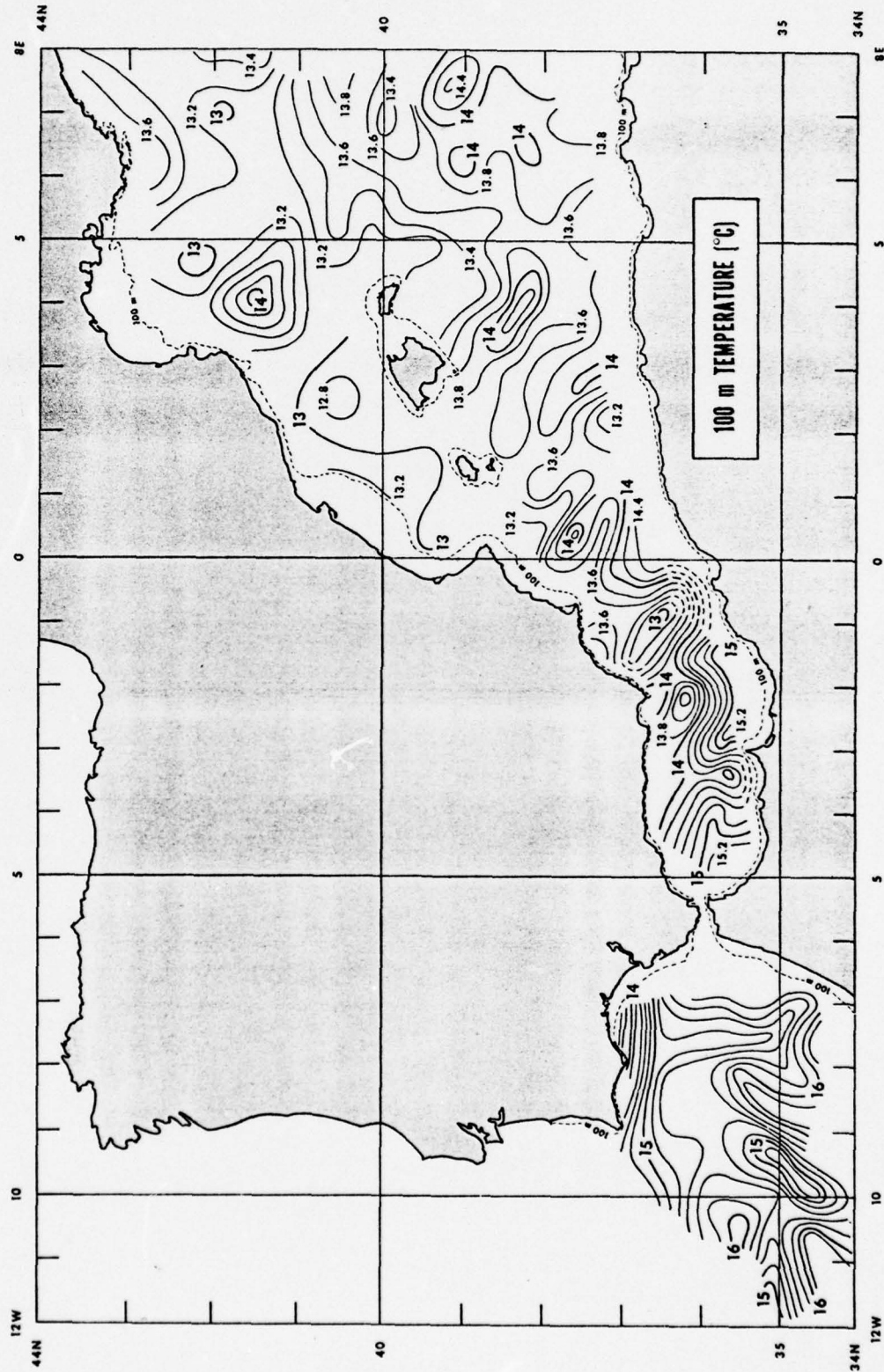


Figure B2 - Temperature at 100 m, 30 April to 8 May 1976

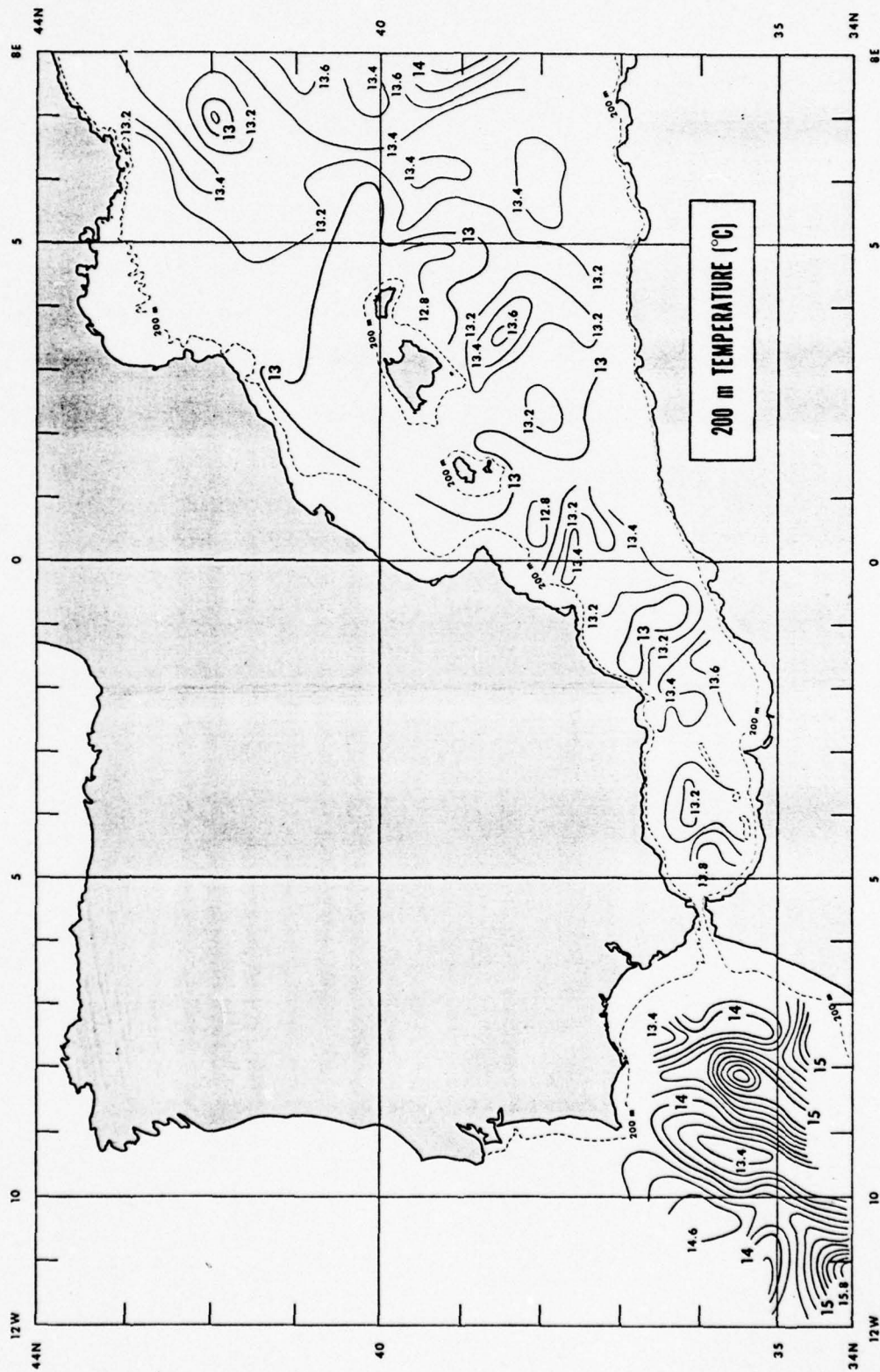


Figure B3 - Temperature at 200 m, 30 April to 8 May 1976.

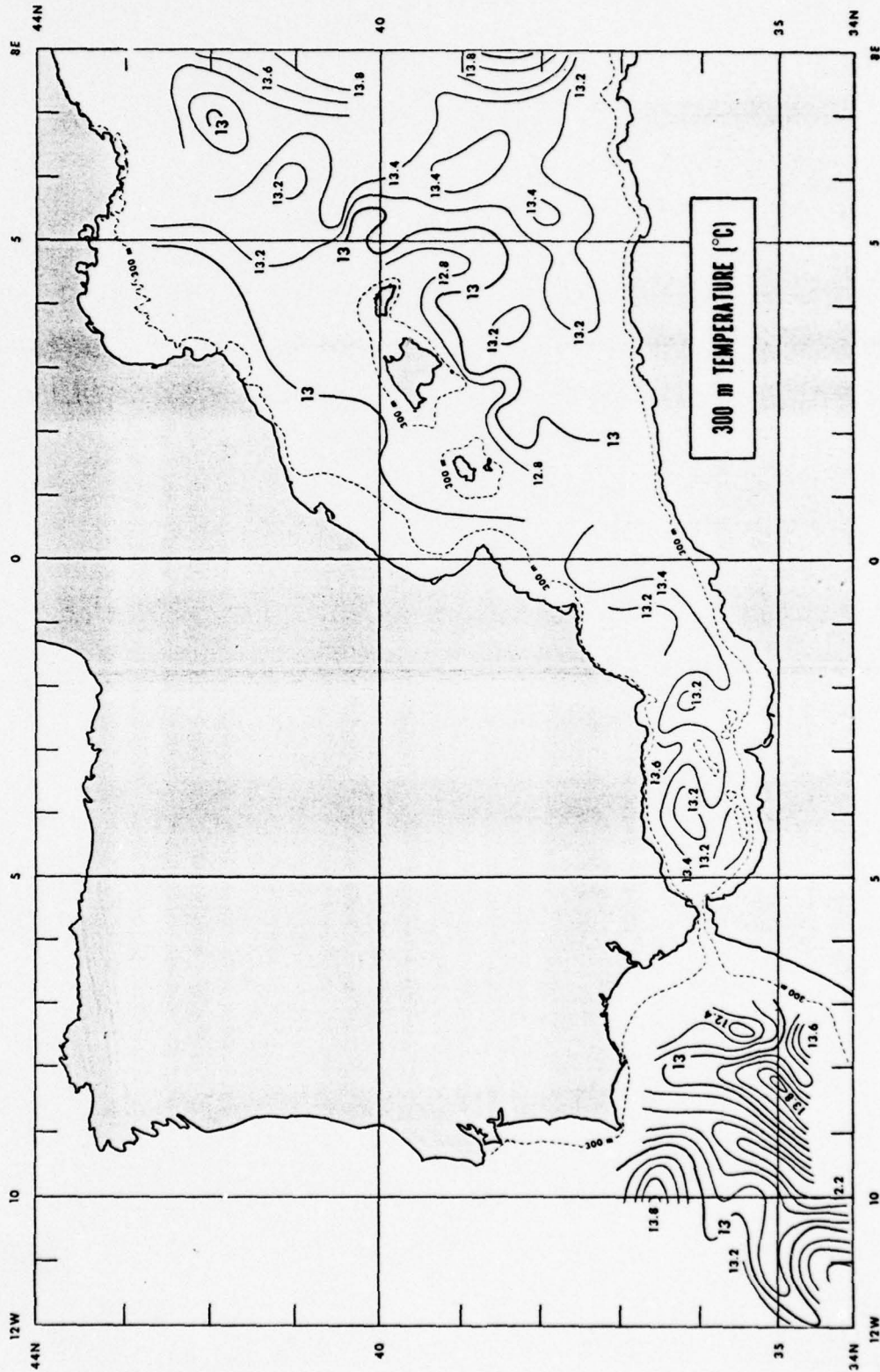


Figure B4 - Temperature at 300 m, 30 April to 8 May 1976.

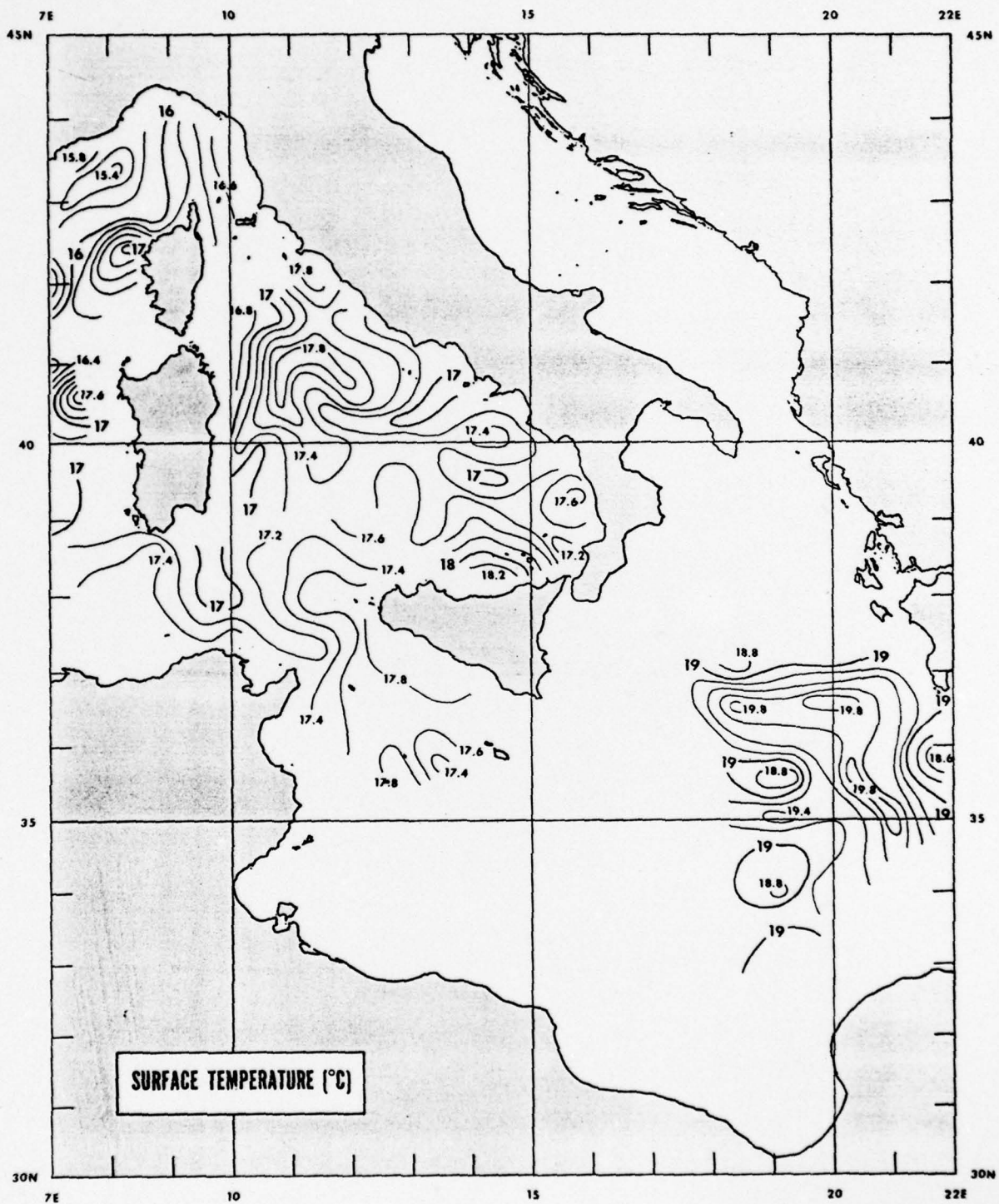


Figure B5 - Surface temperature determined from AXBT's, 10-19 May 1976.
Isotherms are at 0.2°C intervals.

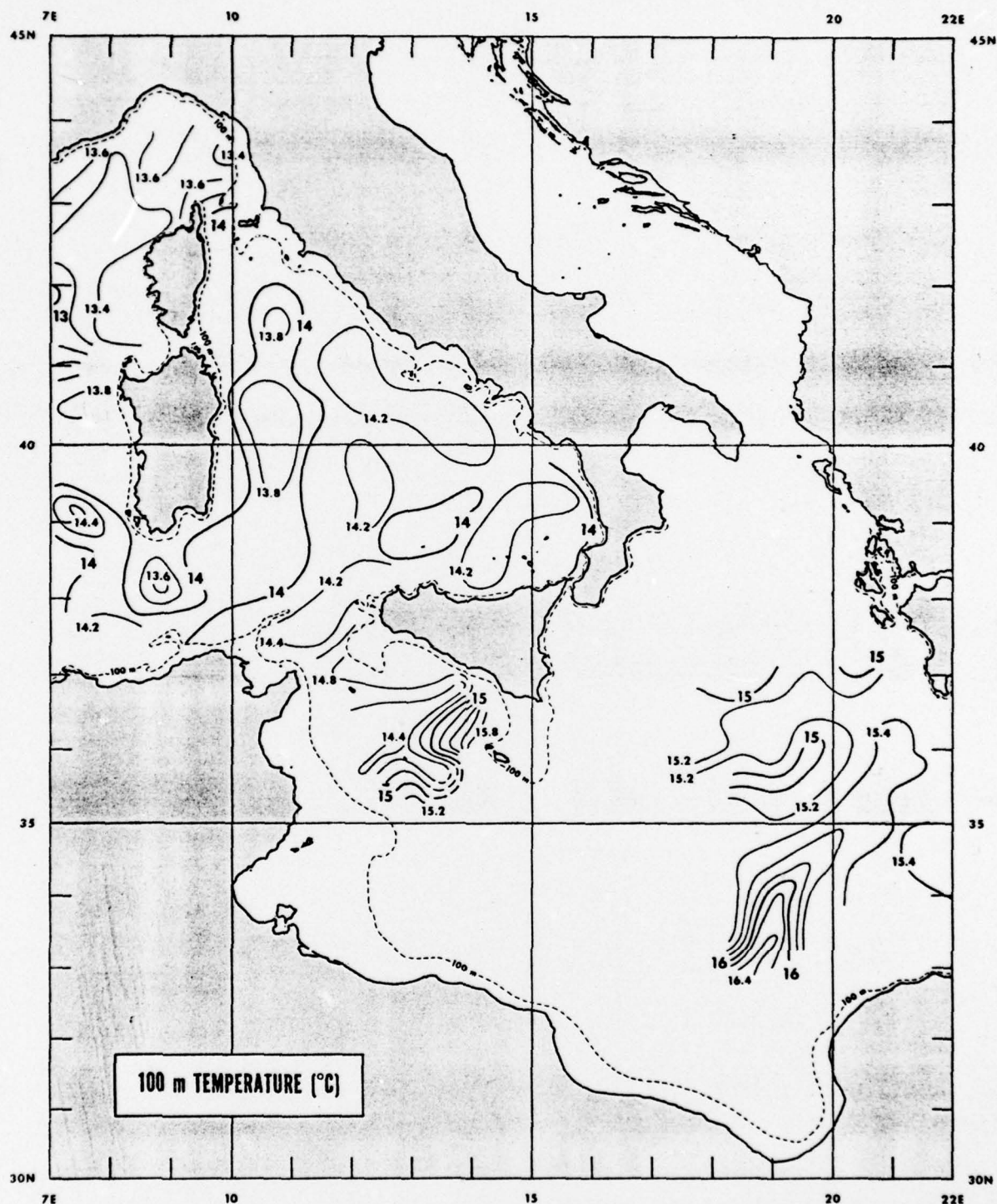


Figure B6 - Temperature at 100 m, 10-19 May 1976.

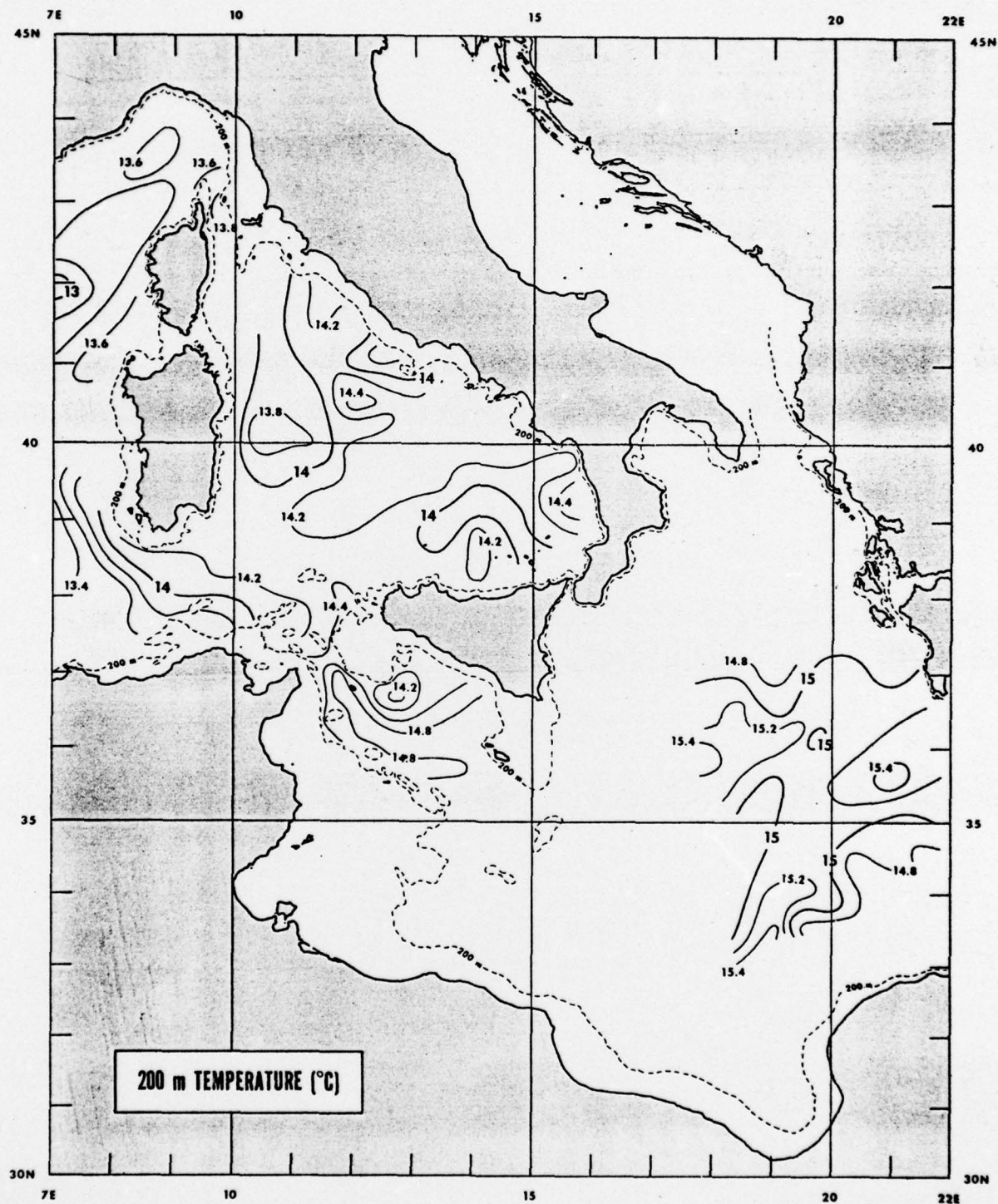


Figure B7 - Temperature at 200 m, 10-19 May 1976.

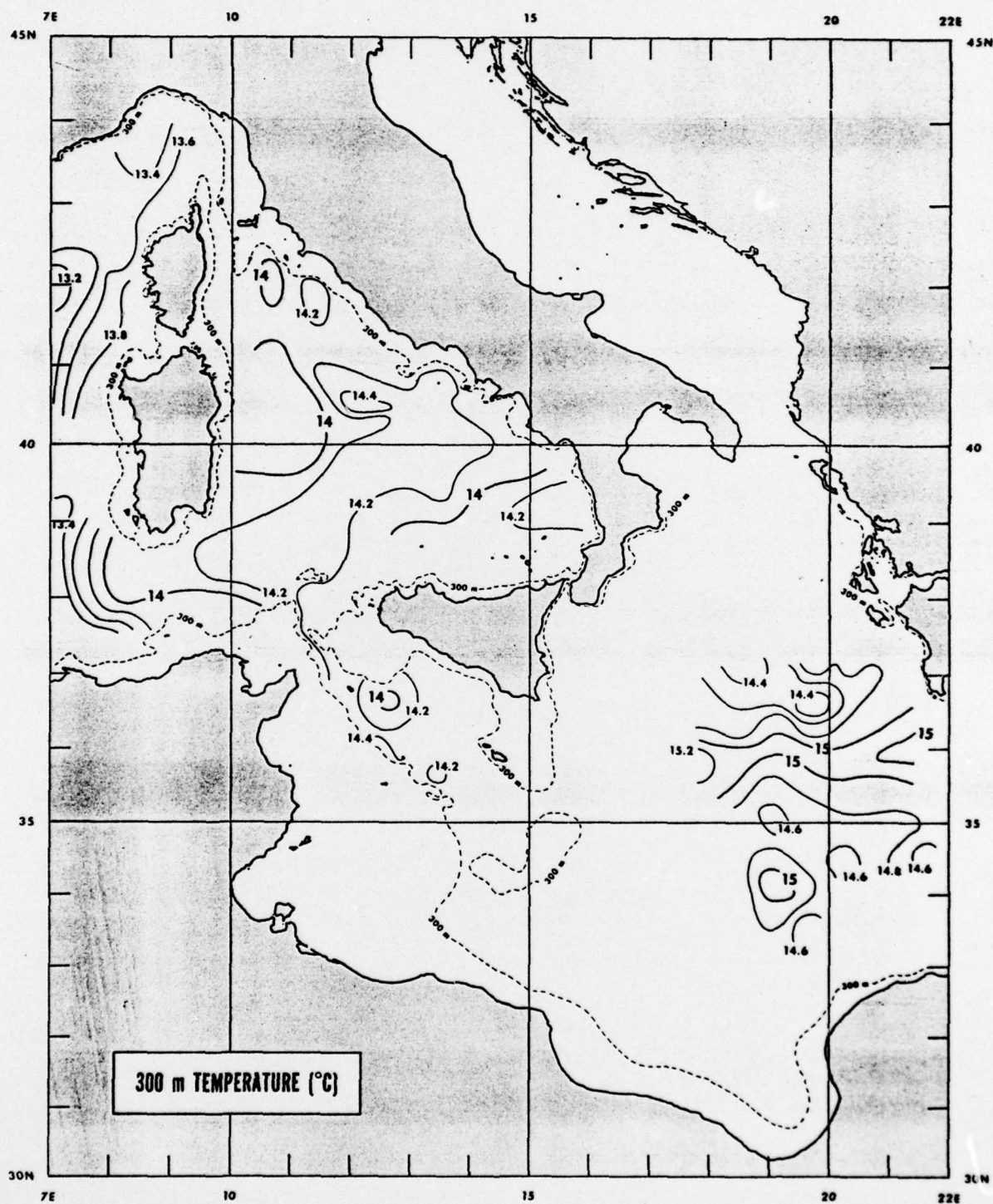


Figure B8 - Temperature at 300 m, 10-19 May 1976.

APPENDIX C

TEMPERATURE SECTIONS AND PROFILES

Representative temperature sections from seven of the basins are shown in Figures C3 through C9; locations of each section are indicated in Figures C1 and C2. AXBT profiles from which the sections were constructed are provided in each figure.

The Gulf of Cadiz (Figure C3) consists of unmodified Atlantic Water and is radically different from the Mediterranean sections. The broad thermocline, characteristics of this water mass, occupies the entire section between the surface and 350 m. At either end of the north-south section steeply sloping isotherms indicate that current flow is toward the east. These two regions of rapid horizontal temperature change appear as meandering frontal zones in the 100 m map (Figure B2).

The Mediterranean sections display several general trends. Progressing from west to east, the seasonal thermocline becomes more intense and moves closer to the surface, producing a corresponding decrease in SLD. As mentioned previously, this is due to the dual effect of differential sampling time and the eastward flowing surface layer. Largest vertical excursions of the thermocline are found in the Alboran Sea (Figure C4), where the undulating isotherms reflect alternating pockets of warm and cool water. In other basins, depth of the thermocline remains more nearly constant.

In most of the areas surveyed, horizontal gradients below the thermocline are small. A majority of the profiles indicate nearly isothermal conditions (Levantine Intermediate Water) at depths greater than 100 m. The most homogeneous water occurs in the Balearic Basin (Figure C6), site of Deep Water formation in winter. Intermediate water displaying the most variability is found in the Sicily Strait (Figure C8) where isolated temperature inversions create significant horizontal gradients. Physical characteristics of this area are complicated by shallow depths and high currents.

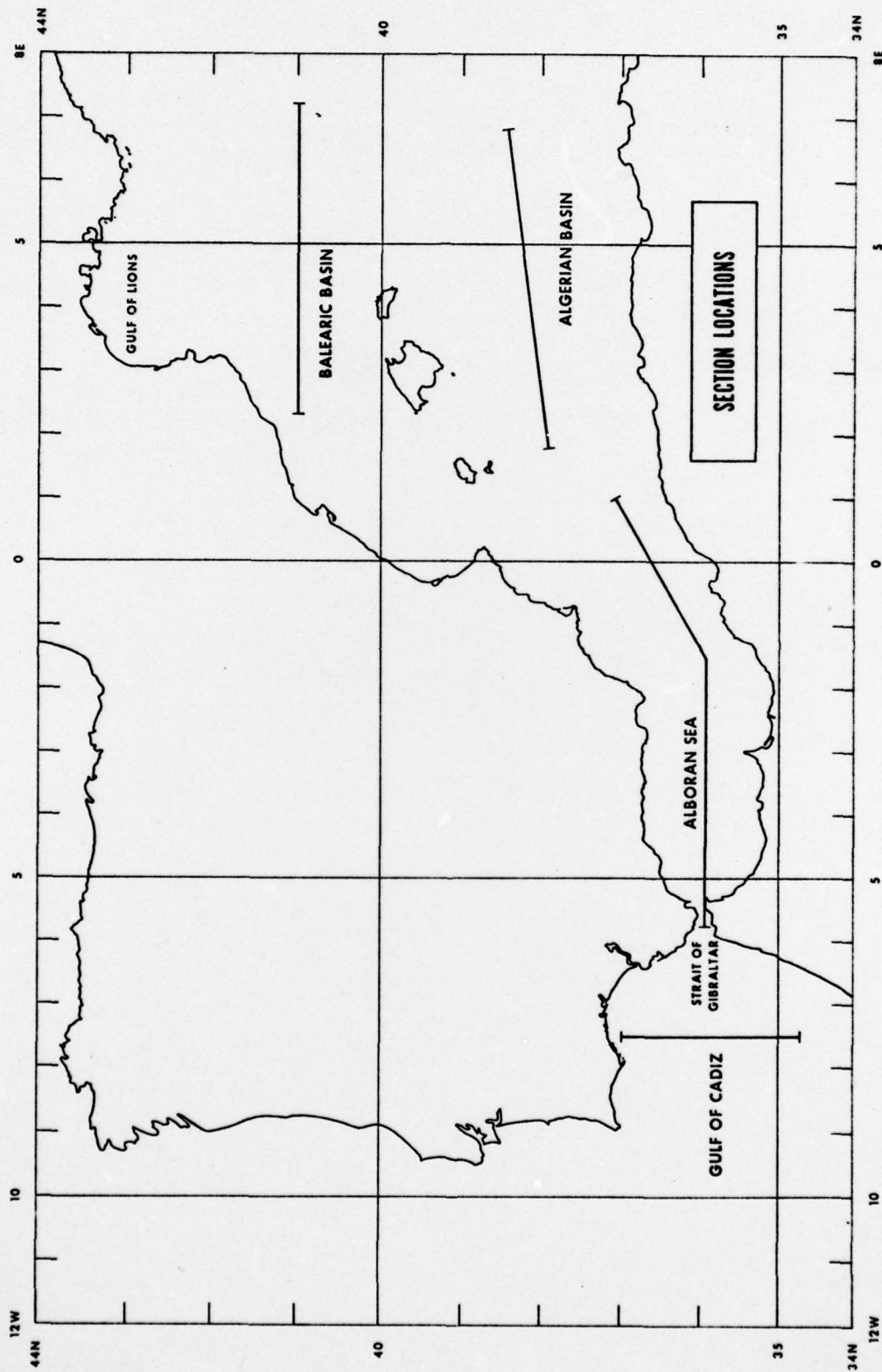


Figure C1 - Locations of temperature sections displayed in Figures C3-C6.

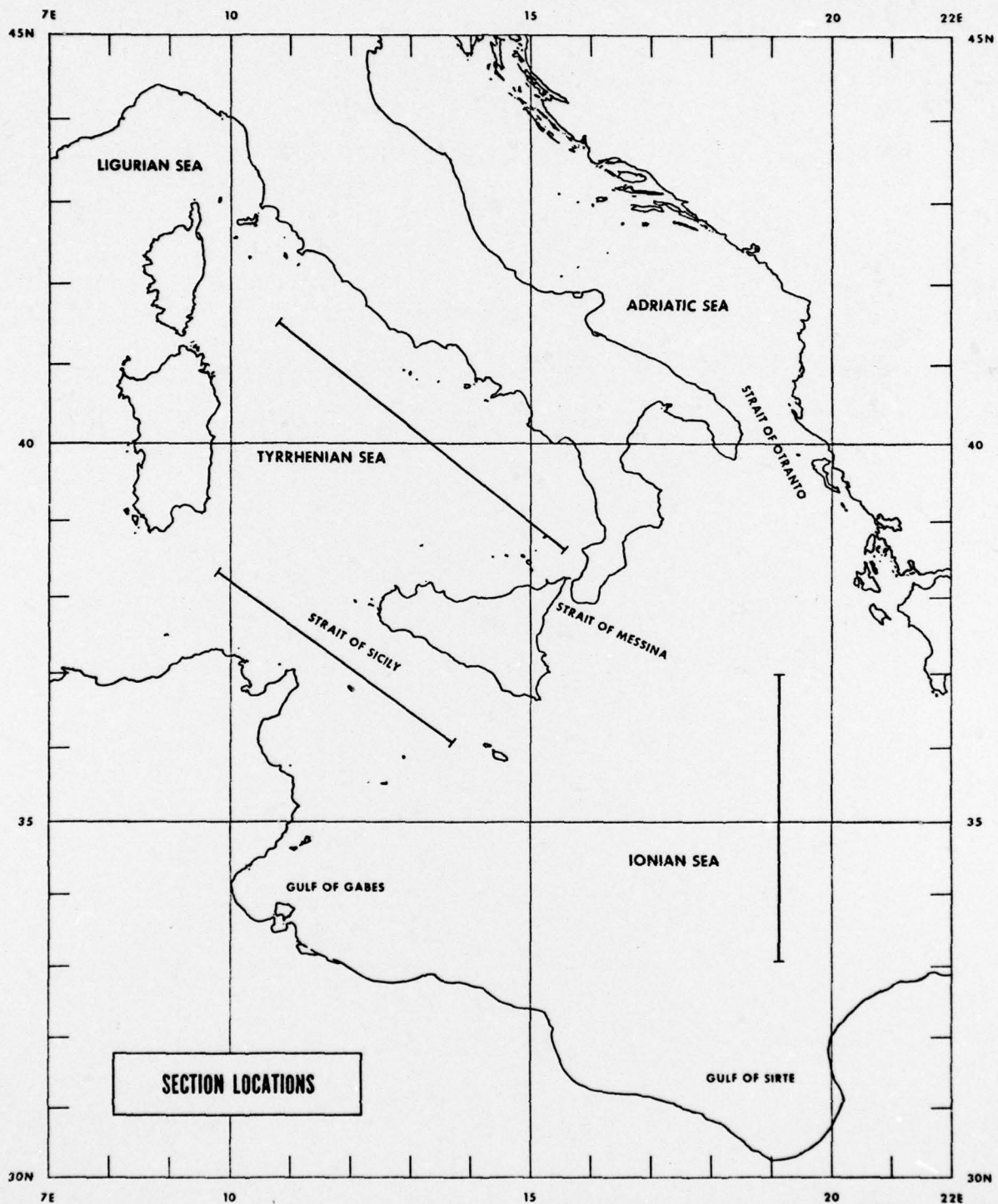


Figure C2 - Locations of temperature sections displayed in Figures C7-C9.

GULF OF CADIZ
30 APRIL 1976

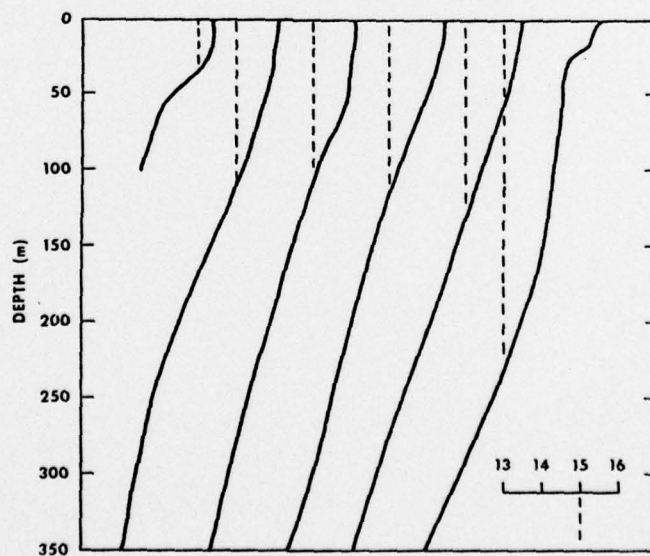
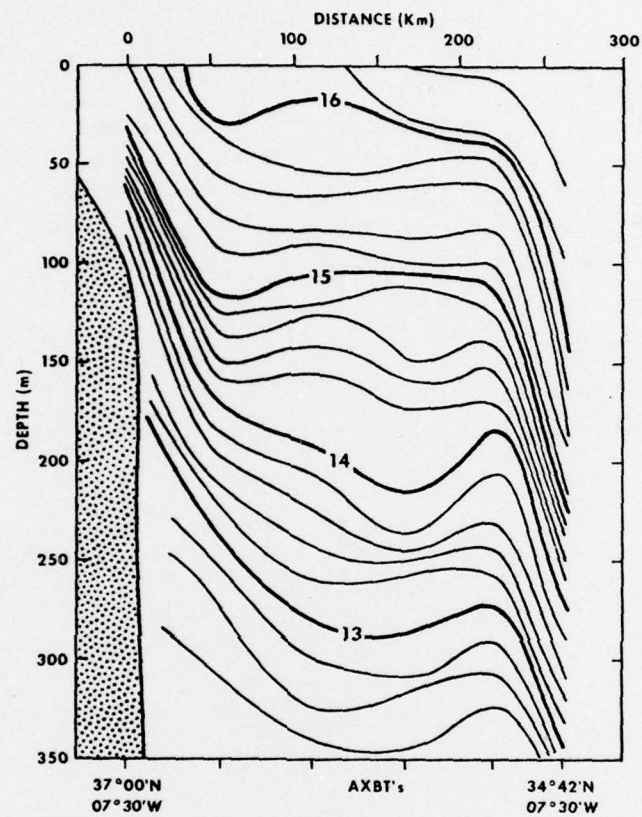


Figure C3 - Gulf of Cadiz temperature section.

ALBORAN SEA
1 MAY 1976

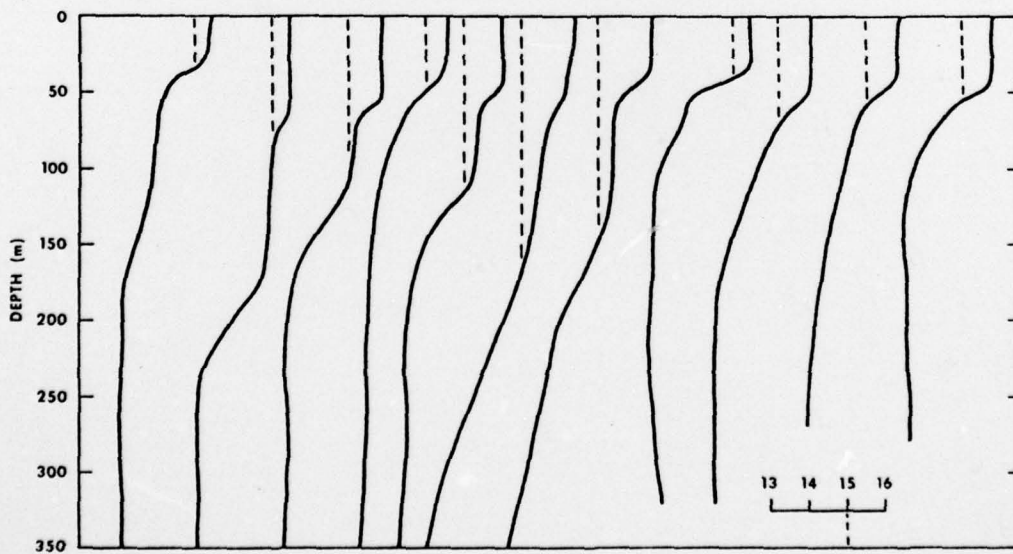
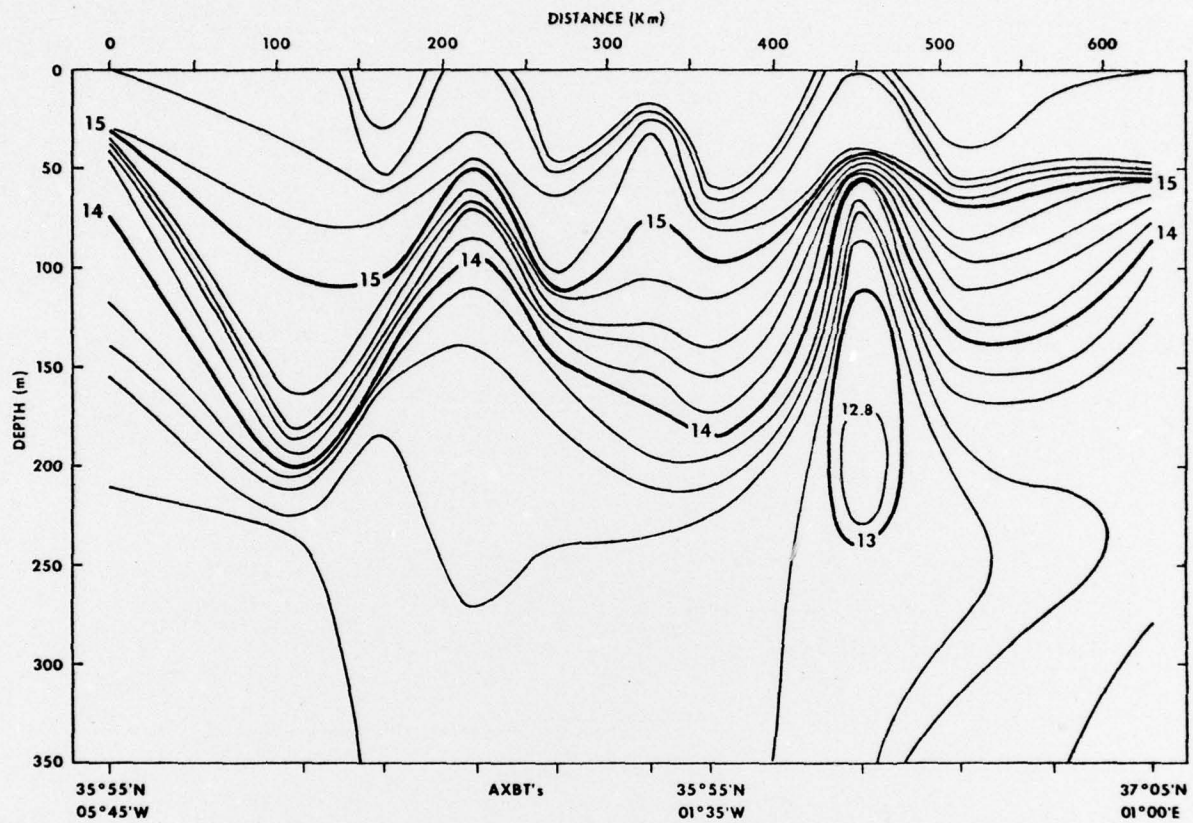


Figure C4 - Alboran Sea temperature section (°C).

ALGERIAN BASIN
8 MAY 1976

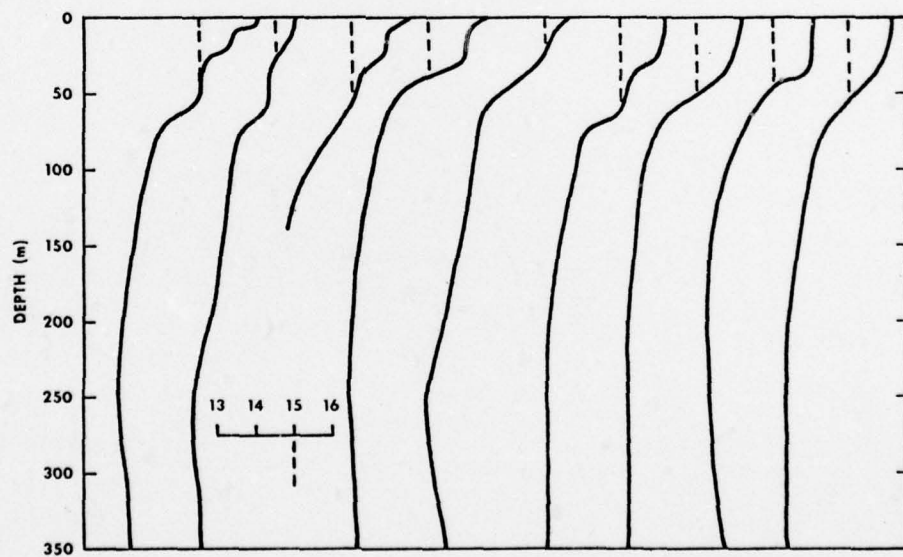
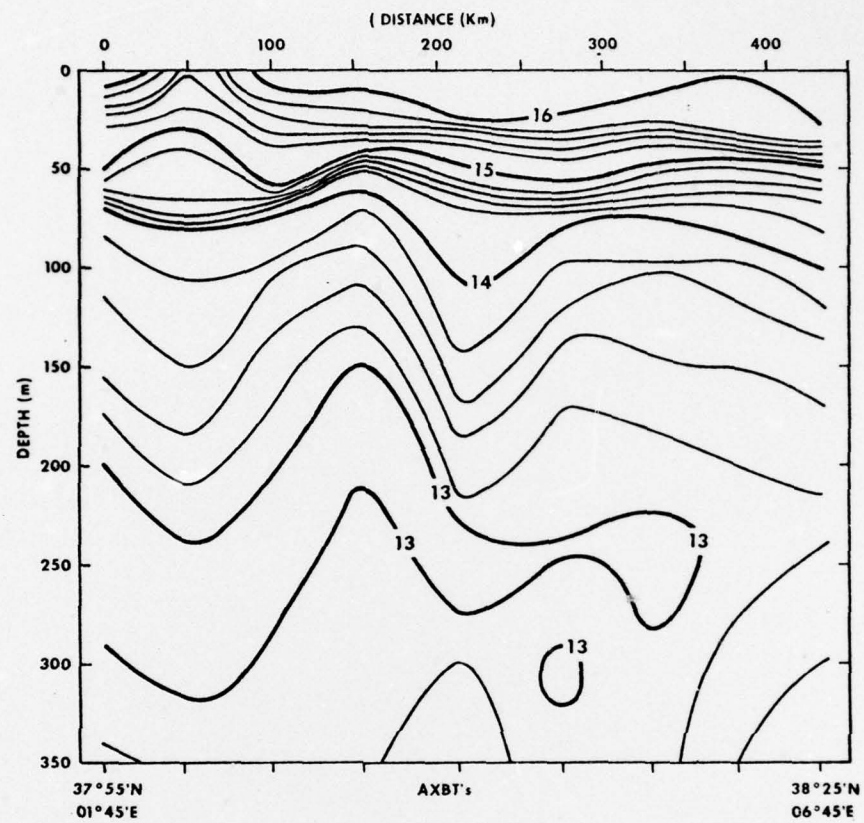


Figure C5 - Algerian Basin temperature section (°C)

BALEARIC BASIN
7 MAY 1976

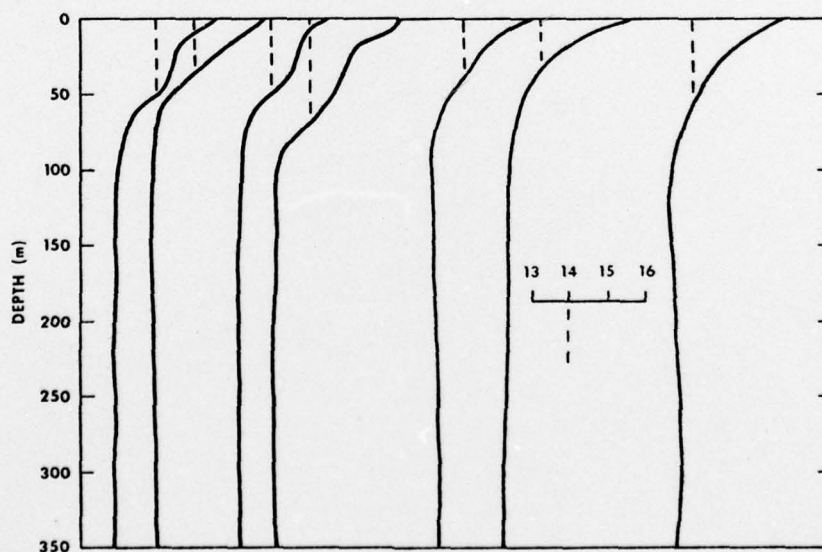
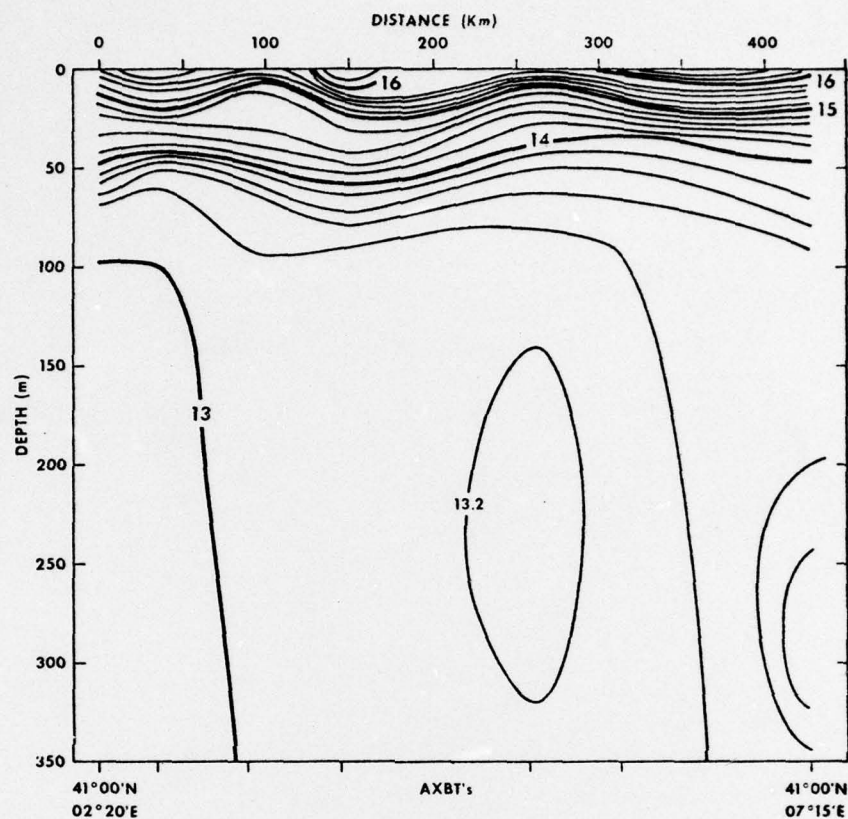


Figure C6 - Balearic Basin temperature section (°C).

TYRRHENIAN SEA
16 MAY 1976

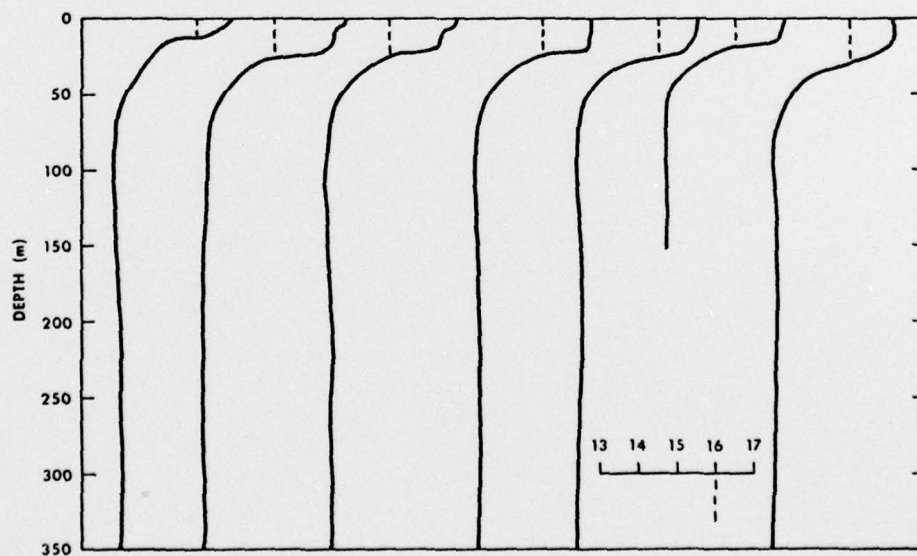
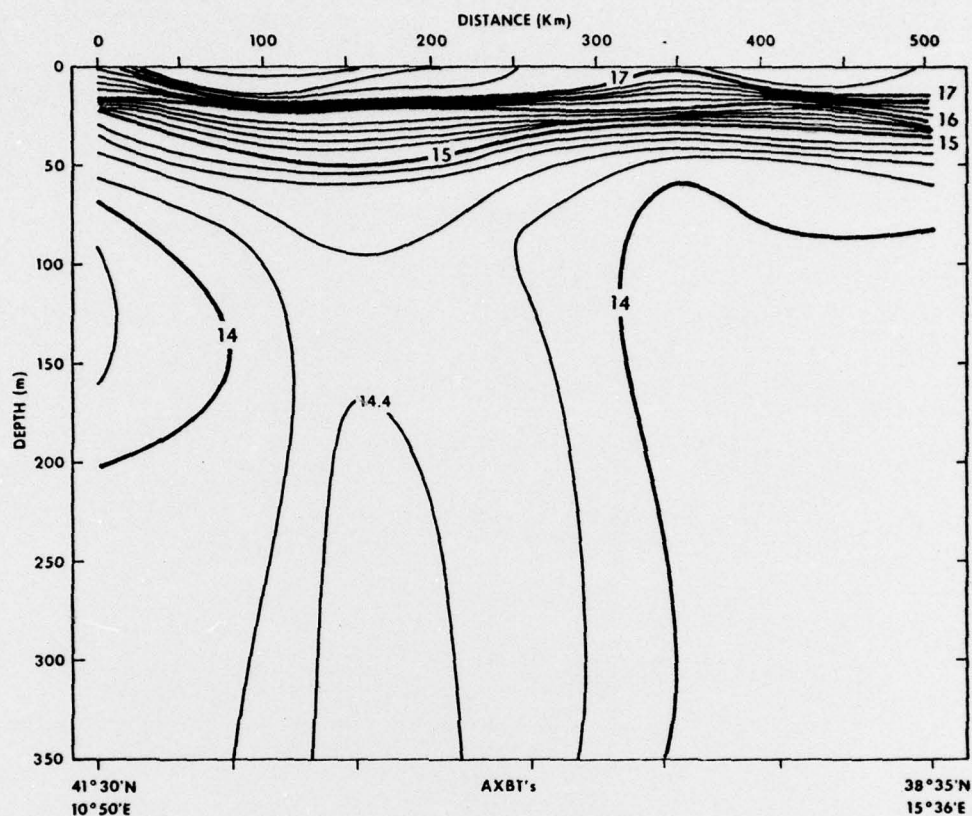


Figure C7 - Tyhrrenian Sea temperature section (°C).

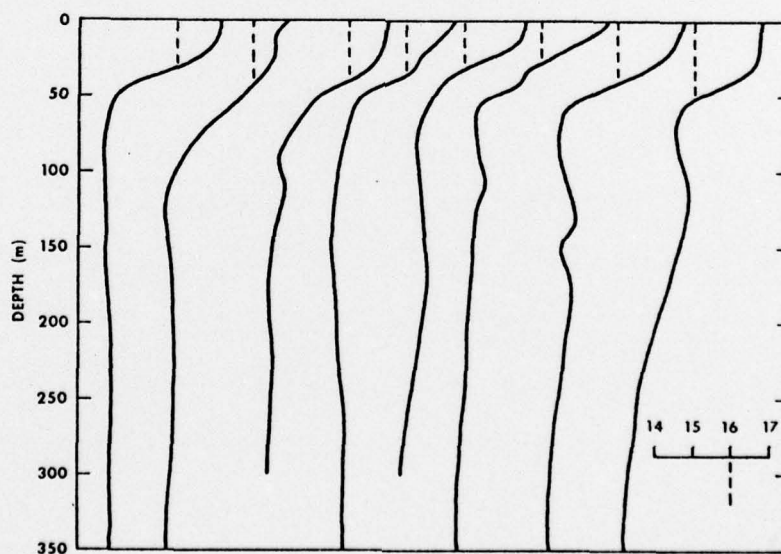
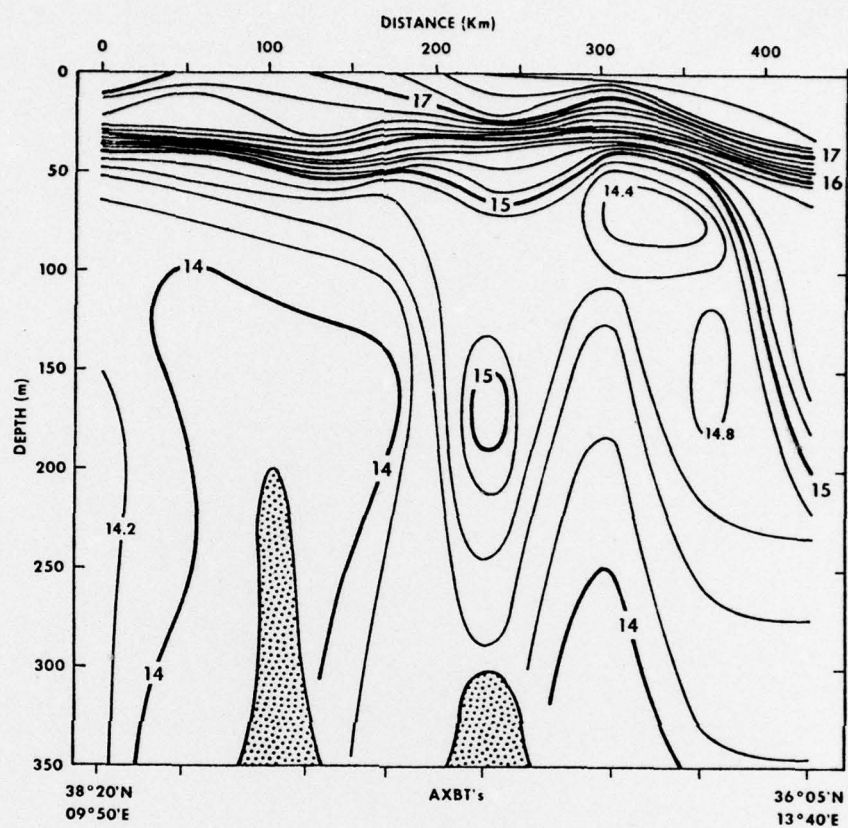
SICILY STRAITS
17 MAY 1976

Figure C8 - Strait of Sicily temperature section (°C).

IONIAN SEA
19 MAY 1976

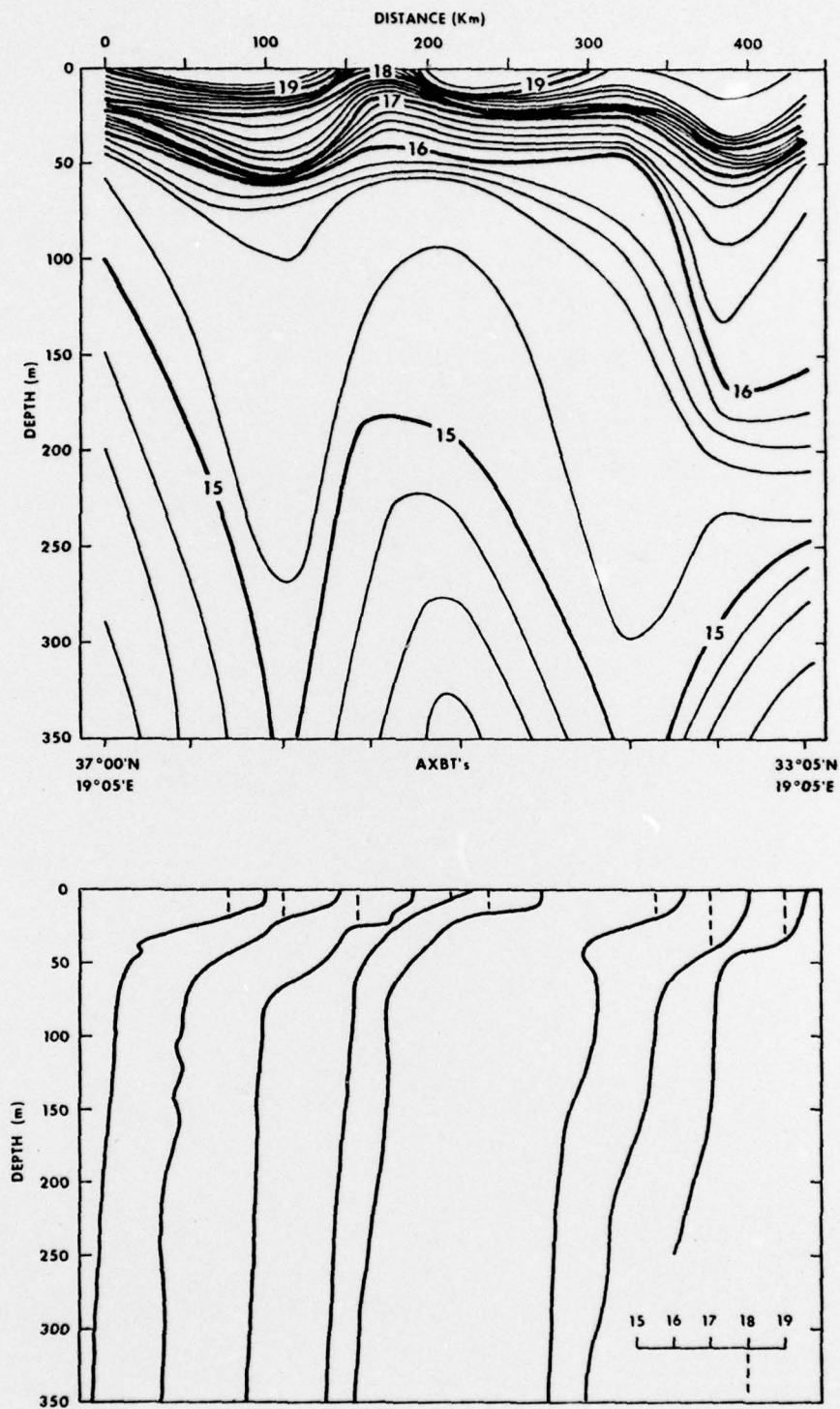


Figure C9 - Ionian Sea temperature section (°C).

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